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MEASUREMENTS OF STRESS AND STRAIN ON CYLINDRICAL TEST SPECIMENS OF ROCK AND CONCRETE UNDER IMPACT LOADING

by

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and

D. L. Birkimer

April 1966

DEPARTMENT OF THE ARMY

Ohio River Division Laboratories, Corps of Engineers

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SUMMARY

A test method to determine the minimum dynamic tensional stress required to rupture materials that have a high compressive strength and a relatively low tensile strength is evaluated. The test loading is by impact from an air-fired projectile. The loading device utilizes a 250-gram projectile, and can produce an impact momentum varying from zero to over three pound-seconds. The rise time of the stressing pulse or shock wave produced in the test pieces is in the order to 20 to 30 microseconds, and the pulse length about 10 inches. The test method considered is based on the measurement of the velocity imparted to a pellet lightly attached to the distal end of a cylindrical test specimen subjected to the impact of an air-fired projectile. This velocity measurement provides the basis for computing the maximum longitudinal stress or strain created in the test specimen by the impact loading. The validity of this test method, which is designated as the "Pellet Technique", is evaluated by attaching strain gages to the test specimens and comparing this direct measurement of maximum longitudinal strain with that indicated by the pellet technique. Comparative measurements of this type were made on cylindrical test specimens of aluminum, quartz monzonite rock, plain concrete, and fibrous-reinforced concrete. There was good correlation between the strains measured directly and those obtained by means of the pellet technique. It is concluded, within certain limitations, that the pellet technique can be used to obtain quantitative values of the dynamic tensile strength for materials that have high compressive strength and relatively low tensile strength.

PREFACE

The development and application of the test procedures described in this report comprise a part of DASA- and Army-sponsored investigational programs concerned with: means of strengthening rock against shock effects, applications of fibrous-reinforced concrete to protective construction, and spalling due to explosive loading. This program is assigned to the Construction Engineering Laboratory of the U. S. Army Engineers Ohio River Division Laboratories (ORDL). The Construction Engineering Laboratory received support for the work described herein from the Physical Tests Branch of the Concrete Laboratory, and from the Instrumentation Branch of the Technical Services Division of the Laboratories.

Engineers of the Ohio River Division Laboratories directly concerned with the developments presented in this report were: F. M. Mellinger, R. L. Hutchinson, G. R. Williamson, and D. L. Birkimer. This report was prepared by F. M. Mellinger and D. L. Birkimer.

During the period covered by the work described in this report, Mr. Frank M. Mellinger was Director of the Ohio River Division Laboratories; Mr. John Merzweiler was Assistant Director.

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MEASUREMENTS OF STRESS AND STRAIN ON CYLINDRICAL TEST SPECIMENS OF ROCK AND CONCRETE UNDER IMPACT LOADING

PART I: INTRODUCTION

Background

1. The determination of failure characteristics of materials under dynamic loads of various types has been studied both theoretically and experimentally for some time. During 1963, the Laboratories was involved in the testing of rock and concrete materials for the construction of deep underground protective structures, and surface structures subject to the explosive hazard of stored munitions. A simple dynamic loading test was needed to compare static and dynamic properties of materials, and to evaluate different types of construction materials that would be required to resist dynamic loads caused by explosive forces. After surveying the literature on the subject, and after discussions with individuals working in this field, an impact type test was selected. There followed the development of an impact loading apparatus utilizing an air-fired projectile. This apparatus was designed for testing cylindrical specimens of rock and concrete. A report of this early development is given in reference 7, entitled "A Method for Determining the Critical Normal Fracture Stress for Rock and Concrete Specimens". The "Critical Normal Fracture Stress" is defined as the maximum tensile stress which a material will tolerate. A more exact definition would be the minimum dynamic tensional stress required to rupture the material. Rinehart[(8)*], in the bulletin entitled "Fractures Caused by Explosions and Impact", gives an excellent treatment of the theoretical background and application for this type of testing. Previous work of this type has been in connection with the testing of metals, except for a recent paper (1965) by Goldsmith et al[(4)] entitled "The Dynamic Behavior of Concrete". Since the earlier report[(7)] of these Laboratories, the loading apparatus has been improved, techniques have been developed for measuring strain in materials loaded dynamically, and a more precise evaluation of the accuracy of the test results obtained from the impact loading test has been made.

Purpose

2. The purpose of this report is to present a quantitative evaluation of a specific type of impact test designed to determine the critical normal fracture stress of materials such as rock and concrete, which have a high compressive strength and a relatively low tensile strength.

*Raised numerals refer to references

Scope

3. This report includes a brief resume of the theoretical considerations involved, followed by detailed description of the loading apparatus and electronic equipment used for measuring pulse velocities and dynamic strains. Strains due to dynamic loading are measured by two methods; one is an indirect method depending entirely on theoretical consideration; while the other is a direct method utilizing strain gages. This report is, in essence, an evaluation of the indirect method. An aluminum bar is instrumented and tested for calibration purposes. Similar tests are made on three other materials; quartz monzonite rock, plain concrete, and fibrous-reinforced concrete. The test results are used to evaluate both the direct and indirect test methods. The limitations and application of the two test methods are discussed and pertinent conclusions given.

PART II: PRINCIPLES INVOLVED IN THE FRACTURE OF MATERIALS UNDER IMPACT OF A HIGH-VELOCITY PROJECTILE

General

4. A compressional wave is induced in a material by striking it with a high-velocity projectile. In this instance, an impact loading device is used with a cylindrical test specimen, as described in Appendix A. At impact, a compressional wave travels from the impact end, approaches the free surface at the opposite end of the specimen, and is reflected at normal incidence. The reflected wave or pulse is tensional. At the time of reflection, there will still be a remnant of the compressional pulse in the material near the end. The maximum stress σ_0 at reflection interferes with the remaining compressional stress σ_I. In this instance, the maximum distance back from the free end that this interference may occur is about one half the pulse length (wave length), depending on the wave shape. If at any time the difference between σ_0 and σ_I exceeds the critical tensile stress " σ_c " of the material, fracture occurs; and a spall will form and separate from the parent material. A number of spalls may form under a single impact. Plate 2b shows multiple spalling of a plain concrete test specimen. Spalling is defined as the formation of a fracture and the separation of the fractured material from the parent material.

Theoretical Considerations

5. If it is assumed: that the test material is isotropic and elastic; that the stress disturbance is a plane wave; that the stress in the transverse direction is not of sufficient magnitude to affect the results; that the stress disturbance or pulse has an instantaneous rise time, with the maximum stress occurring at the leading edge of the wave; and that the particle velocity is not changing with respect to time; according to Kolsky[6], the longitudinal stress caused by a plane wave traveling along a cylindrical bar is given by the following relationship.

$$\sigma_x = \rho C_x V \qquad (1)$$

where

σ_x = the longitudinal stress
ρ = the mass density of the material
C_x = seismic or phase velocity of the material
V = the particle velocity

If the particle velocity induced by the stress disturbance is known, then the longitudinal stress can be computed by equation (1) for a given material, or the strain can be computed by the following formula:

$$\epsilon_x = \frac{V}{C_x} \qquad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

Measurements

6. Two methods are used to measure the longitudinal stress or strain in a cylindrical test specimen subjected to high-velocity impact loading by the device described in Appendix A. The first method is an indirect method, indicated as the pellet technique, making use of equations (1) and (2). The second method is the direct measurement of strain by means of electrical strain gages and the electronic equipment described in Appendix B.

a. Pellet Technique. A small pellet, which is characteristically impedence-matched to the material, is lightly attached to the distal end of the test piece with moisture. The test piece is ballistically suspended as close as possible to the end of the firing tube (see Plate A-1, a). When the end of the cylindrical specimen is impacted by the projectile, the pellet will be separated from the specimen by the impulse trapped in it from the pulse created by the impact. On the basis of the assumptions outlined in the preceeding paragraph, the particle velocity induced in the specimen by the impact is equal to one half the pellet velocity. When the particle velocity is known, the stress or strain induced in the test piece can be computed from equations (1) or (2). It is realized that for materials such as rock or concrete, the induced pulse does not precisely conform to the assumptions on which equations (1) and (2) are based. However, some meaningful correlation with measured strain under identical load conditions indicate that these highly idealized assumptions apply, to some extent. The minimum dimensional requirements are that the length of the test specimen be slightly greater than the length of the induced wave. This will assure ample distance for the tensional wave to reach its maximum value before interference from any transverse disturbance occurs. A length-diameter ratio of the test piece of 5 or greater facilitates the production of a plane wave. Actual measurement of the pellet velocity is accomplished by illuminating a scale and pellet by a strobe light, and photographing the moving pellet with a polaroid camera aligned at right angles to the projected axis of the test specimen. The strobe light frequency is determined by means of the Universal Eput Timer. Knowing the strobe light frequency and the scale dimensions, the pellet velocity can be obtained from the photographed trace of the pellet. A typical trace is shown on Plate 1b. Here, the pellet is seen to travel 0.0927 feet in 1/200 of a second. The resulting pellet velocity is 18.54 ft/sec., giving a particle velocity of 18.54/2 or 9.27 ft/sec.

b. Direct Strain Measurements. The strain gages are located on the test specimens to measure longitudinal strains under the dynamic loading of the impact device. The read-out apparatus, described in Appendix B, gives the strain at the gage location with respect to time. The strain due to the compressional wave, and the reflected tensional wave or pulse, were successfully recorded in most instances for all materials tested. A study of these strain-time relationships also provided an indication of the rise time and pulse length for the type of impact loading used. Plate 1a shows a typical oscilloscope record photograph from two strain gages mounted diametrically opposite each other, 4.5 inches back from the distal end of a cylindrical 2 x 10-inch long plain concrete test specimen.

PART III: COMPOSITION AND PHYSICAL PROPERTIES OF TEST SPECIMENS

General

7. Table 1 summarizes the average physical properties of five materials used for the specimens tested by the impact loading device. The specific gravity and seismic velocity measurements were made on each test specimen. The values for the Dynamic "E_d" Youngs modulus were computed from the following formula:

$$E_d = \rho C_x^2 \qquad \text{.} \ (3)$$

where

ρ mass density
C_x seismic velocity

The mass density is the specific gravity of the material divided by the acceleration due to gravity. The seismic velocity is determined by measuring the fundamental frequency "f" with a sonometer equipped with a cathode ray tube. The seismic velocity is then obtained from the following relationship:

$$C_x = 2 \ell f \qquad \text{.} \ (4)$$

where

C_x = seismic velocity in ft/sec
ℓ = specimen length in feet
f = fundamental frequency in cycles per second.

The static Youngs Modulus was determined from direct tension tests, using metalectric strain gages. Plots of the stress strain curves for the plain concrete, concrete reinforced with nylon fibre, and concrete reinforced with steel fibre, are given by Figures 1 - 3. The tests were made on specimens, 10.25 inches long, by 2 inches in diameter. Steel caps were cemented to each end of the specimen with an epoxy system. The tensile load was applied through attached flexible wire cables, appropriately gripped in a universal testing machine. Strain was measured as the average of three equally spaced gages at the longitudinal center of the specimen. A similar procedure was followed for determining the static Youngs Modulus for the quartz monzonite rock[5].

Concrete Test Specimens

8. General. The same basic mixture was used for the plain and fibrous-reinforced concrete specimens. Its proportions by weight were 1:2.47, with a water cement ratio of 0.46. The aggregate gradation was:

Sieve	% Retained
No. 8	5
No. 16	23
No. 30	32
No. 50	30
No. 100	8
Pan	2
Fineness Modulus	2.81

9. Fibrous-Reinforced Concrete. The following tabulation gives the pertinent information on the composition of the fibrous-reinforced concrete.

Table A

Fibres Used for Reinforcement

Fibre	Size		by volume, %
	length, in.	dia. in	
Nylon	1.5	0.010	1.25
Steel Wire	1.5	0.017	1.25
Asbestos	KB-438-4T		1.25

The above fibres were combined with the basic concrete mix described in the preceding paragraph.

10. Test Specimens. The test specimens were cast in brass molds 11 inches long, and 2 inches in diameter. The concrete was consolidated by external vibration. Specimens were wet cured for seven days, and all testing was accomplished between 7 and 10 days. The specimens were prepared for testing by trimming each end with a precision diamond saw to give a final length of 10.25 inches, with squared ends.

11. Tension Tests. The tensile strength of the concrete given in Table 1 is an average of two tests. Tests were performed on 2-inch diameter, by 10.25-inch long specimens, prepared as indicated in the preceding paragraph. The nylon, steel wire, and asbestos fibres in the reinforced specimens failed in

bond. In no case was failure of the individual fibres observed.

12. Compression Tests. The compressive strength of the concrete, given in the next to the last column of Table 1, are 7-day strengths obtained from 2 x 2-inch modified cubes.

Discussion

13. The static and dynamic properties of the aluminum bar and the quartz monzonite rock were quite similar, except with regard to tensile strength. The Dynamic Youngs Modulus was essentially the same as the static modulus, for both the aluminum and the rock. This was also true for the plain concrete. This is an indication of the relative homogeneity of these materials. Apparently the No. 8 maximum size aggregate in the concrete did not cause too much discontinuity in the material; since for concrete with larger size aggregate, the static modulus is generally about 1×10^6 psi less than the dynamic modulus. This latter is true for the nylon and steel wire reinforced specimens. No static values of Youngs Modulus were obtained for the concrete reinforced with asbestos fibre. The lower dynamic values obtained may have been due to the character of the asbestos fibres, and more particularly to the fact that the asbestos fibres absorbed water; it was necessary to use additional water to maintain a workable mix. In the case of the tensile strengths, one would normally expect the strength of the concrete reinforced with wire fibres to be greater than the strength of the concrete reinforced with nylon fibres for the same fibre quantities and dimension. This is true for the flexural strength [3]. One possible explanation for the greater tensile strength of the nylon reinforced concrete is that the orientation and distribution of the nylon fibres in the test specimens was better than that of the steel wire for this particular size specimen.

PART IV: ALUMINUM BAR TESTS

General

14. Initially, tests were made on an aluminum bar, 12 inches long by 1.375 inches in diameter, to check out the strain-recording equipment, and to obtain information on the pulse length and its rise time. Seven strain gages were placed at 1-inch intervals, starting at the distal end of the bar. Four tests were made. The firing pressure for the projectile was 10 psi for the first three tests, and 30 psi for the fourth test (see Table 2). Projectile velocities were not measured; however, an approximation of the projectile velocity can be obtained from the calibration curve of Figure A-1. For each test, measurements of strain and pellet velocities were obtained.

Test Results.

15. Pellet Technique. Measurements of particle velocity were obtained as indicated in paragraph 6a. Table 2 gives the firing pressure and particle velocities measured for each test, and the pertinent physical properties of the aluminum bar. From these, the values of induced stress and strain are computed, and are shown in the fourth and fifth columns of Table 2. For a firing pressure of 10 psi, the computed stress in the bar was in the order of 5000 psi, and the strain was 520 micro-inches per inch. At a firing pressure of 30 psi, the stress indicated was 18,500 psi, and the strain 1920 micro-inches per inch.

16. Direct Strain Measurements. The strain gage measurements for each of the four tests are shown on Figures 4 through 7. The magnitude of the strain measured on each of the seven gages is shown on the ordinate scale, with respect to time in micro-seconds on the absissa. The origin, with respect to the ordinate scale, is the initial part of the trace, and indicates the zero setting of the measuring apparatus. Strains below this reference are negative (compressive); those above this reference are positive (tensile). The strains selected as being most representative of the strain measured by the pellet technique are the initial peak compressive strains measured by gages 1 and 2, which are seven and six inches from the distal end of the bar. These range from 500 to 550 micro-inches per inch for the 10-psi firing pressure, and about 1920 micro-inches per inch for the 20-psi firing pressure.

Discussion

17. Comparisons of Maximum Tensile Strains Indicated by the Pellet Technique and Direct Strain Measurements. If it is assumed as reasonable that

the maximum strain indicated by the initial compression pulse is reflected without attenuation from the distal end of the bar, the comparison between the tensile strain indicated by the pellet technique is remarkably good. The pellet technique indicates a maximum tensile strain of 520 micro-inches per inch for the three tests at a 10-psi firing pressure, while direct maximum strain measurements range from 500 to 550 micro-inches per inch. At a 30-psi firing pressure, the pellet technique indicates a strain of 1920 micro-inches per inch, while the direct maximum strain measured is in the order of 1900 micro-inches per inch. Even though the maximum measured strains used in the above comparison were measured at only one circumferential location on the surface of the aluminum bar, it can be tentatively concluded that the pellet technique will give a reasonably accurate measurement of the maximum tensile stress or strain under these conditions of impact loading.

18. Pulse Characteristics. The pulse characteristics indicated by the transducers located near the mid point of the bar are quite uniform for all four tests. The rise time indicated in Figures 1 through 4, using the initial compression pulse for the first two or three transducers, is about 25 micro-seconds; i. e., the time between its start and arrival at a peak strain value. This can also be shown on Figure 1, by noting that gage No. 1 shows a peak strain value; while at the same time, the strain at gage 6 is approximately zero. The distance between gages 1 and 6 is 5 inches. The longitudinal wave velocity C_X for the aluminum bar is 16, 000 ft per sec. If 5/12 is divided by 16, 000, one obtains about 26 micro-seconds. Figures 2 - 4 indicate essentially the same condition for gages 1 and 6. The strain time curves on Figures 1 through 5 indicate the time from the start of the pulse until its decay to be in the range of 50 to 60 micro-seconds. If these times are multiplied by 16, 000 ft per sec. (the longitudinal wave velocity), pulse lengths of 8. 4 and 9. 6 inches are indicated. This would indicate that the length of test specimens for the type of impact loading employed should be at least 10 inches long in order to develop maximum strains well away from the impact end, and to produce reliable measures of maximum stress or strain using the pellet technique. When strain gages are used to record maximum tensile strains, they should be located between 4. 5 and 5. 0 inches back from the distal end of a 10-inch or longer test piece.

PART V: TESTS OF QUARTZ MONZONITE ROCK

General

19. Two specimens of quartz monzonite rock were instrumented and tested. Specimen No. 1 was 2.4 inches in diameter, and 8.5 inches long; specimen No. 2 was 2.4 inches in diameter, and 10.4 inches long. The ends of each specimen were squared by a cut from a precision diamond saw, and further squared by hand-lapping. Three tests were made on Specimen No. 1. The firing pressure for the projectile was 10 psi, giving a velocity of about 25 ft per sec. The second specimen was subjected to two tests. For the first test, the firing pressure for the projectile was 10 psi, and for the second it was 14 psi. At the latter firing pressure, which produced a projectile velocity of about 35 ft per sec., the specimen failed in tension.

Instrumentation

20. Only one gage used on each specimen was calibrated to measure strain with respect to time. This gage was of the type described in Appendix B. These gage locations are given in Table 1. For Tests 1B1 and 2B1, two Glennite ceramic strain gages were mounted on the specimen diametrically opposite each other as indicated by gages 2 and 3 on Figures 9 and 12. These gages are specially designed for measuring the timing and passage of shock waves; but are not calibrated to give quantitative values of strain. The particular gages used were Type SC-1, and are 3/8-inches long by 1/16-inch wide. For Specimen No. 1, the ceramic strain gages were located 2.8 inches from the impact end of the specimen; for Specimen No. 2, the ceramic strain gages were located 3.5 inches from the impact end. These gages were intended to provide information on the rise time and length of pulse produced in the specimens by the impact loading device.

Test Results

21. For each test, the particle velocity was measured by the pellet technique, and the strains measured at the location of the attached transducers with respect to time.

a. Pellet Technique. Th· ›article velocities measured for each test are given in the fourth column of Table 4. The stresses and strains obtained from these velocities are given in columns 5 and 6 of this tabulation. For Specimen No. 1, using a projectile firing pressure of 10 psi, the induced stress ranged from 2850 to 3580 psi with a range of strain from 273 to 344 micro-inches per inch for the three tests. For Specimen No. 2, the stress at the 10-psi firing

pressure was 2500 psi, and the strain 227 micro-inches per inch. At the firing pressure of 14 psi, the stress was 5840 psi and the strain 530 micro-inches per inch; a tensile failure occurred at a distance of 5.25 inches from the distal end of the specimen.

b. Direct Strain Measurements. As indicated previously, strains were measured with respect to time at only one point on the surface of the test specimens. The strain time curves for each test are given by gage 1 on Figures 8 through 12.

c. Dynamic Wave Form of Strains. The ceramic strain gages, used in Tests 1B1 and 2B2, were not calibrated to measure strains. However, they did provide insight into the rise time and pulse length as well as correspondence of the wave form at two points on the surface of the specimen diametrically opposite each other. These measurements are given by gages 2 and 3 on Figures 9 and 12.

d. Specimen Condition Under Repeated Impact Loading. Aside from the 5.25-inch long spall that occurred for test 2B1, no critical damage of the test specimens was observed to have taken place. At the impact end of the specimen, a small amount of chipping occurred; but no crushing.

Discussion

22. The test results presented in the preceeding paragraphs are most interesting from the standpoint of the pulse or wave characteristics indicated, the comparison of strains measured directly with those obtained by the pellet technique, and the failure characters of the quartz monzonite in test 2B1.

a. Pulse Characteristics. The pulse characteristics are best examined by the use of Figures 9 and 12, showing the curves obtained from both the calibrated strain gage and the two ceramic gages. The ceramic gages in both instances (for firing pressures of 10 and 14 psi) indicate the total rise and decay time of the initial pulse to be about 40 micro-seconds, with some indication that the decay time is less than the rise time. The calibrated gages (Gage 1) indicate a total rise and decay time of the initial pulse to be 55 to 60 micro-seconds. Using an average seismic velocity of 17,000 ft per sec for the material, this would indicate that the pulse or wave length indicated by the ceramic gages was about ($40 \times 10^{-6} \times 17,000 \times 12$) 8 inches; while for the regular strain gages, indicating a maximum of 60 micro-seconds, the pulse length would be about 12 inches. The properties of the quartz monzonite rock, which would have an effect on the pulse length under these loading conditions, are similar to those of the aluminum bar; where pulse lengths of 8 to 10 inches were indicated. Since specimens for this type of loading and measurements (max. stress and strain) should be at least as

long as the pulse length, the 8.5-inch specimen may be too short; however, further correlation does not give this impression.

b. Comparison of Direct Strain Measurements with Strains Obtained by the Pellet Technique. The direct strain measurements, that are considered to be most comparable with maximum tensile strain or stress indicated by the pellet technique, are the initial maximum compressive strains measured by the strain gages on the surface of the specimens. These strains obtained from Figures 8 - 12 are listed for each test in column 7 of Table 4. They compare quite well with those strains measured by the pellet technique. (See column 6 Table 4) Neither method is precise as the basic figures are obtained from photographic scales in both cases. For example, the trace on Figure 8, test 1b, has no clearly defined zero reference. In this case, an initial maximum compressive strain of about 337 micro-inches per inch was obtained by assuming that the rise time was 25 micro-seconds. This is also true in the case of Figure 10 test 1B2, where the initial maximum compressive strain is estimated to be about 287 micro-inches per inch. Probably one of the best comparisons to examine is that obtained for test 2B1. In this one instance, the reflected tensile strain measured by the single strain gage on the surface of the test specimen is practically equal to the initial compressive strain. The order of magnitude is 500 micro-inches per inch, as compared to a maximum tensile strain of 530 micro-inches per inch obtained by the pellet technique.

c. Failure Characteristics. Quartz monzonite rock fails in direct tension, under static loadings, at strains in the range of 160 to 170 micro-inches per inch[5]. Under the dynamic impact loading, the rock did not fail at tensile strains in the order to 200 to 300 micro-inches per inch. However, it did fail at an indicated tensile strain of about 500 micro-inches per inch (see test 2B1).

d. Critical Normal Fracture Stress. Rinehart[8] defines the critical normal fracture stress as the maximum tensile stress a material will tolerate, or more exactly, the minimum dynamic tensional stress required to rupture the material. One of the objectives of this study is to evaluate the application of the pellet technique for the measurement of the critical normal fracture stress of materials such as rock and concrete. As previously pointed out, formulas (1) and (2), used to convert particle velocities to stresses and strains, are based on highly idealized assumptions. So far, there has been good agreement between the direct measurement of strain by the transducers and those obtained by the pellet technique. The shock wave or pulse produced by the impact device has a very short rise time; the ceramic gages in tests 1B1 and 2B2 indicate a plain wave, and the wave, and the wave length is such that for the length of specimen used the reflected tensional pulse can attain its maximum value within the central portion of the test specimen. The pellet technique provides a measure of

only the maximum tensile stress induced by the projectile loading. When a test specimen fails by spalling under an impact loading, the indicated maximum tensile stress is not necessarily the critical normal fracture stress for the material. The critical normal fracture stress is obtained by making a number of tests on similar test specimens using a range of projectile impact velocities such that some produce failure and some do not; then the critical normal fracture stress will be somewhere between the greatest maximum tensile stress that does not cause failure and the smallest maximum tensile stress that does cause failure or spalling of the test specimen. For example, in the case of the quartz monzonite rock, the greatest stress that did not cause failure was 3580 psi (test 1B); and the stress measured for the only failure that occurred (test 2B1) was 5840 psi (see col. 5, Table 4). If only the pellet technique had been used, and these were the only available test results, it would be necessary to say that the critical normal fracture stress for the quartz monzonite rock was somewhere between 3600 and 5800 psi. However, referring to Figure 12, it can be seen that failure occurred (5.25-inch long spall) right at the recording strain gage. Looking at the strain time curve for this gage, it will be seen that the material withstood the full tensional pulse for the first cycle; and failure occurred during the second tensional pulse. Also, the magnitude of the maximum compressive strain is essentially the same as the maximum tensile strain. Therefore, it is likely that in this instance the critical normal fracture stress is about 5800 psi as measured by the pellet technique. The maximum measured strain is 500 micro-inches per inch (see Figure 12). If this strain is multiplied by the dynamic modulus of elasticity for the material, a stress of 5500 psi is obtained. Previous tests[5] of quartz monzonite rock, using only the pellet technique to measure the maximum stress, indicated no failure or spalling at a stress of 4700 psi. The use of the pellet technique along with the impact loading device to measure the critical normal fracture stress does at least provide a quantitative answer that is dependent on the number of tests made and the uniformity of the test specimen used. In some cases, it may be possible to only establish a range or approximation of the critical normal fracture stress. It is interesting to compare the critical normal fracture stress, or dynamic tensile strength, of the quartz monzonite rock with its static tensile strength. Table 1 gives a value of 1400 psi for the static tensile strength of the quartz monzonite rock. This indicates that the dynamic tensile strength (critical normal fracture stress) of this material is in the range of three to four times its static tensile strength.

PART VI: TESTS OF PLAIN AND FIBROUS REINFORCED CONCRETE

General

23. Impact loading tests have been made on plain, nylon-fibre-reinforced, steel-fibre-reinforced, and asbestos-fibre-reinforced concrete specimens. For each test, measurements of strain by the pellet technique and by direct measurement with strain gages were made. In all cases, the test specimens were 10.25 inches long and 2.0 inches in diameter. Three tests were made on each of two plain concrete specimens. Both specimens were loaded to failure on the third test. Three specimens of nylon-fibre-reinforced concrete were used. Two of the specimens were loaded to failure on the initial test, and two tests are reported for the third specimen with no failure.

24. Two specimens of steel-fibre-reinforced concrete were tested. Failure was produced by the initial loading on the first specimen (Wp-5). Four tests were made on the second specimen, with failure taking place during the fourth test. Results are given only for tests 2 and 4 on this specimen.

25. Four tests were made on one asbestos-fibre-reinforced concrete specimen. None of the four test loadings caused failure.

26. The test conditions for all concrete test specimens are given in Table 5. This table gives the firing pressure of the projectile for each test, as well as the number and location of the strain gages used on each test specimen. Where failure occurred, the length of spall is given in the last column of this table.

27. As indicated previously, the average physical properties of the various types of concrete are given in Table 1. The mass density "ρ" and the seismic velocity "C_x" are given in columns 2 and 3 of Table 6 for each test specimen.

Test Results

28. Pellet Technique. Column 5 of Table 6 gives the particle velocities measured by the pellet technique for each test. The following two columns give the stress and strain computed from the particle velocity by means of equations (1) and (2).

29. Direct Strain Measurements. Figures 13 - 28 give the measured strain for each test with respect to time. Figures 13 - 17 apply to the plain

concrete, Figures 18 - 21 apply to the nylon-fibre-reinforced concrete, Figures 22 - 24 apply to the steel-wire-fibre-reinforced concrete, and Figures 25 - 28 apply to the asbestos-fibre-reinforced-concrete test specimens.

30. Failure Conditions. In all tests, the impact of the projectile caused some degree of crushing on the impact end of the test specimens. This can be seen to some extent on the photograph of Plate 2b. This plate also shows multiple spalling produced in a plain concrete specimen. The failure surfaces of the spalls are quite irregular in comparison with those for the quartz monzonite rock. In the case of the plain concrete, the spall completely separates itself from the parent material; and will have a velocity similar to that of the pellet, if it is a first spall. However, in the case of the nylon-fibre- and steel-fibre-reinforced concrete specimens, spalling was only evidenced by the formation of an irregular hairline crack around the periphery of the test specimens, with no further separation. This can be seen on specimens 13 and 14 of Plate 2b. Plate 3 shows a photomicrograph of such a crack as it appeared on the cylindrical surface of a fibrous-reinforced concrete specimen. Once a spall of this type occurred on a fibre-reinforced specimen, further loading at higher impact velocities still would not produce separation of the spall from the parent material It appeared that for the fibre-reinforced concrete specimens, only the mortar matrix failed with only a slight bond failure of the fibres. There also appeared to be little difference between the critical normal fracture stress of the plain and fibre-reinforced concrete. This will be discussed in more detail later on.

Discussion

31. The points of chief interest in these tests are the pulse characteristics of the impact load, failure of the materials, a comparison between the strain indicated by the pellet technique and that measured directly by the strain gages, and an estimate of the critical normal fracture stress of the materials.

a. Pulse Characteristics. The rise time and the length of pulse indicated by the strain time curves for the plain, nylon-fibre-reinforced, and steel-fibre-reinforced concrete specimens are similar to that indicated by the aluminum bar and quartz monzonite rock tests. However, the initial rise time and length of the pulse is about twice as great for the asbestos-fibre-reinforced concrete. This is probably due to the fact that this concrete is weaker in compression than the other concrete (see Table 1), and a greater amount of crushing occurred at the impact end of the specimen. Further evidence of a square wave front is the production of multiple spalling in the plain concrete (see Plate 2b). Multiple spalling was also produced in the quartz monzonite rock under high impact loading.

b. Tests of Plain Concrete Specimens. In comparing the measured strains with those indicated by the pellet technique, good agreement

was obtained in the tests of the aluminum bar and the quartz monzonite rock by using the maximum measured strain indicated by the initial compression pulse. The following table makes this comparison, using the maximum measured strain for the initial compression pulse, and the first tensional pulse given by the strain time curves of Figures 13 - 17 for the plain concrete specimens. Where there are two recording gages diametrically opposite each other, the strains given are average of the two gages in both the compression and tension phase.

Table B

Comparisons of Maximum Strains in Plain Concrete Test Specimen

Test No.	Projectile Firing Pressure psi	Max. Strain, Micro-inches/in.			Length of Spall, in.
		Pellet Technique	Measured		
			Compr.	Tension	
Wp2-1	8	320	375	300	None
Wp2-2	10	530	560	460	None
Wp2-3	12	680	-	-	4.5
Wp7-1	8	360	610	375	None
Wp7-2	10	460(3)	950	525	None
Wp7-3	12	820	1400	750(1)	5.5(2)

(1) one gage only.
(2) spall 1 inch back of gage (see Fig. 17).
(3) pellet improperly fastened.

It will be seen from Table B that for the first two tests, Wp2-1 and Wp2-2, there is a reasonable agreement between the pellet strain and the measured maximum compressive strain. However, the agreement is better for the Wp7 series, if maximum average measured tensional strains are compared with the pellet strains. Test Wp7-1 compares better with Wp2-1 for the 8-psi firing pressure, if the measured maximum tensional strain is used. Test Wp7-2 shows a maximum measured tensional strain of 525 micro-inches per inch. In this case, the pellet was improperly fastened during the test; and from the measurement standpoint, the tensional value may be the more correct selection. In the case of test Wp7-3, the maximum measured tensional strain given is represented by only one gage; the tensional record of the other gage was apparently affected by the failure or spall which occurred about one inch back of the gage (see Figure 17). The pellet technique indicates a critical normal fracture strain

falling between 530 and 680 micro-inches per inch (see tests Wp2-2 and Wp2-3). Referring to Table 6, this shows no failure at a stress of 2500 psi; and failure at a stress of 3210 psi. This indicates that the critical normal fracture stress is greater than 2500 psi, but less than 3210 psi, for the limited number of tests made on the plain concrete.

c. Tests of Nylon-Fibre-Reinforced Concrete. The following tabulation is prepared on the same basis as that for the plain concrete specimens shown by Table B. The measured strains given in Table C were obtained from Figures 18 - 21.

Table C

Comparisons of Maximum Strains in Nylon-Fibre-Reinforced Concrete Test Specimens

Test No.	Projectile Firing Pressure, psi	Max. Strain, Micro-inches/in. Pellet Technique	Measured Compr.	Measured Tension	Length of Spall, in.
Wp3	20	1290	1200	- - (1)	4.5
Wp4	16	1120	1075	525(2)	3.0
Wp9-2	10	660	950(3)	650(3)	None
Wp9-3	8	282	325(3)	225(3)	None

(1) Failure at gage
(2) Spall one inch ahead of gage (see Figure 19).
(3) One gage.

The above tabulation indicates reasonably good agreement between the pellet technique and measured maximum strains, if the initial compression phase is used for Tests Wp3 and Wp4. In the case of test Wp9-2, the agreement is better if the measured maximum tension strain is used for the comparison. Test Wp9-3 indicates poorer agreement, regardless of whether the compressive or tensional phase is used for the comparison. This may be due to the crushing effect that the 10-psi test had on the specimen for test Wp9-2, which was made before the specimen was subjected to the 8-psi firing pressure for test Wp9-3. This crushing of the end of the specimen could have affected the pellet reaction in both cases, since Wp9-2 represents the second test made on this specimen. Test Wp9-1 is not reported. On the basis of the pellet technique, the greatest stress at which the nylon-fibre-reinforced concrete did not fail was 3250 psi, see Table 6 (Test Wp9-2). This value also checks reasonably well with the measured maximum tensional strain, given in Table C for this same test (Wp9-2). However, the measured maximum strains in the compression and

was obtained in the tests of the aluminum bar and the quartz monzonite rock by using the maximum measured strain indicated by the initial compression pulse. The following table makes this comparison, using the maximum measured strain for the initial compression pulse, and the first tensional pulse given by the strain time curves of Figures 13 - 17 for the plain concrete specimens. Where there are two recording gages diametrically opposite each other, the strains given are average of the two gages in both the compression and tension phase.

Table B

Comparisons of Maximum Strains in Plain Concrete Test Specimen

Test No.	Projectile Firing Pressure psi	Max. Strain, Micro-inches/in. Pellet Technique	Measured Compr.	Measured Tension	Length of Spall, in.
Wp2-1	8	320	375	300	None
Wp2-2	10	530	560	460	None
Wp2-3	12	680	-	-	4.5
Wp7-1	8	360	610	375	None
Wp7-2	10	460(3)	950	525	None
Wp7-3	12	820	1400	750(1)	5.5(2)

(1) one gage only.
(2) spall 1 inch back of gage (see Fig. 17).
(3) pellet improperly fastened.

It will be seen from Table B that for the first two tests, Wp2-1 and Wp2-2, there is a reasonable agreement between the pellet strain and the measured maximum compressive strain. However, the agreement is better for the Wp7 series, if maximum average measured tensional strains are compared with the pellet strains. Test Wp7-1 compares better with Wp2-1 for the 8-psi firing pressure, if the measured maximum tensional strain is used. Test Wp7-2 shows a maximum measured tensional strain of 525 micro-inches per inch. In this case, the pellet was improperly fastened during the test; and from the measurement standpoint, the tensional value may be the more correct selection. In the case of test Wp7-3, the maximum measured tensional strain given is represented by only one gage; the tensional record of the other gage was apparently affected by the failure or spall which occurred about one inch back of the gage (see Figure 17). The pellet technique indicates a critical normal fracture strain

tensional phase for Test Wp4 indicates a critical normal fracture strain of 550 micro-inches per inch. This value is obtained by assuming that full magnitude of the compressional pulse is reflected from the distal end of the test specimen. Then, since the spall fracture occurred ahead of the gage (see Figure 19), the approximate strain at which the fracture occurred would be the maximum compressive strain (1075 micro-inches per inch) minus the residual tensional strain (525-micro inches per inch), measured by the gage on the parent material after the spall had occurred. Multiplying this strain by the Dynamic Youngs Modulus (4.5×10^6 psi) of the material, gives a critical normal fracture stress of 2470 psi.

d. Tests of Steel-Fibre-Reinforced Concrete. The following Table D, prepared for the steel-wire-reinforced concrete is similar to Table B and C for the plain- and nylon-reinforced-concrete respectively. The measured strains given in Table D were obtained from Figures 22 - 24.

Table D

Comparisons of Maximum Strains in Steel-Wire-Fibre-Reinforced Concrete Specimens

Test No	Projectile Firing Pressure psi	Max. Strain, Pellet Technique	Micro-inches/in Measured		Length of Spall, in.
			Compr.	Tension	
Wp5	20	1570	1350	750(1)	3.0
Wp11-2	8	- -	175	375	None
Wp11-4	14	800	1300	1300(2)	5.25

(1) Spall 1.5 inches ahead of gage (see Figure 22).
(2) Spall 1 inch back of gage (see Figure 24).

Test Wp5 shows fair comparability between the maximum strain obtained by the pellet technique and that measured in initial compression by the strain gages. For test Wp11-4, the comparison is poor. This was the fourth test of the Wp11 series on the same specimen, and it is likely that the crushing effect of the three previous tests on the impact end of the specimen influenced the pellet velocity. However, the measured maximum strains in both the initial compression and tensional phases are identical (see Figure 24), and are therefore more indicative of the actual strain than the strain shown by the pellet technique. Test Wp5 gives an indication of the critical normal fracture strain from the measured strains. It will be noted that for test Wp5, the spall occurred ahead of the strain gages (see Figure 22). Therefore, as in the case of test Wp4 for the nylon-reinforced concrete, the measured maximum tensional strain can be subtracted

from the maximum measured compressional strain to obtain an indication of the critical normal fracture strain. This is (1350-750), or 600 micro-inches per inch. The critical normal fractur^ stress indicated is then 600 x 10^{-6} x 4.8 x 10^{-6} or 2880 psi, where 4.8 x 10^{6} is the Dynamic Youngs Modulus of the test specimen.

e. Tests of Asbestos-Fibre-Reinforced Concrete Specimens. The following Table E compares the maximum strains indicated by the pellet technique and those measured by the strain gages. The table is prepared in the same manner as Table B, C and D. The measured strains given in Table E were obtained from Figures 25 - 28.

Table E

Comparisons of Maximum Strains in Asbestos-Fibre-Reinforced Test Specimens

Test No.	Projectile Firing Pressure psi	Max. Strain, Micro-inches/in: Pellet Technique	Measured: Compr.	Measured: Tension	Length of Spall, in.
Wp12-1	10	665	1020	5[illegible]	None
Wp12-2	8	495	900	500	None
Wp12-4	10	550	960	400	None
Wp12-5	10	665	1240	650	None

The comparison between the strains indicated by the pellet technique and the maximum measured compressive strains is consistantly poor; however if the maximum measured tensional strains are used, the comparison is quite good, with the exception of test Wp12-4. On the basis of the pellet technique, the greatest stress that the asbestos fibre withstood without spalling was 2180 psi, with a corresponding strain of 665 micro-inches per inch (see Table 6, Test Wp12-1 and Wp12-5). The measured maximum tensional strain obtained from the gages also gives essentially the same stress (see Table E, Test Wp12-5).

f. Static and Dynamic Failure Conditions. The foregoing discussions provide a reasonably good indication of the stresses and strains at failure for dynamic loading in tension for the various types of concrete tested. They also provide a basis for selecting quantitative values for comparison with corresponding properties of these materials under static loading. It is realized that the number of tests is limited, but previous experience with these materials and the types of tests involved warrant some tentative conclusions based on their

static and dynamic properties. The following Table F summarize these properties which have been given and discussed previously.

Table F

Comparison of Static and Dynamic Properties

Type of Concrete	Strain and Stress at Failure in Tension			
	Static Loading		Dynamic Loading	
	Strain, Micro-inches/in	Stress, psi	Strain, Micro-inches/in	Stress, psi
Plain	112	491	>530	>2500
Nylon Fibre Reinforced	200	647	550-660	2470-3250
Steel Fibre Reinforced	164	590	600	2880
Asbestos Fibre Reinforced	-	-	>650	>2180
Quartz Monzonite Rock*	165	1400	500	5500

*Included for comparison.

It will be noted from Table F that there is not the same variation between the dynamic properties of the plain concrete and fibre-reinforced concrete that there is in their static properties. The critical normal fracture stress appears to be essentially the same for the plain concrete and the fibrous-reinforced concrete. This supports the observation of the mode of failure given in paragraph 30, wherein for the plain concrete, the spalls at failure separated from the parent material; while for the fibrous-reinforced specimens, the spall remained and was held in close contact with the parent material by the fibre reinforcement which did not fail. Therefore, as indicated in Table F, there is not the large variation between the dynamic strength of the plain concrete and fibre-reinforced concrete that occurs for the static strengths. That is, the only variation in the dynamic strengths is due to a difference in strength of the mortar matrix and the measurements. The ratio between the static strength and dynamic strength of the plain concrete appears to be 1 to 5 or greater while, for the fibre-reinforced specimens this ratio will be less due to the additional mobilization of the bond strength of the fibres in the static tests.

PART VII: SUMMARY AND DISCUSSION

General

32. It should be realized that the testing and results reported herein are exploratory; and as a result, only a few measurements have been made. Only the firing pressure for the projectile is given, along with a calibration curve for velocity determinations. As can be seen from the scatter of points on this curve (Figure A-1), velocities so obtained will be approximate; and the firing pressures for the projectile indicate relative magnitudes. It would also have been desirable to use at least three gages, 120^{o} apart, at uniform spacing along the length of the test specimens. Generally, for the tests, a single gage or two gages diametrically opposite each other were used; and in some cases, located at different distances from the ends of the test specimens. However, in spite of this, the measurements correlate reasonably well; and provide a good insight into the limitations, as well as the advantages, of using the pellet technique for measuring the critical normal fracture stress of materials that have high static compressive strengths and relatively low tensile strengths, such as rock and concrete. This, in turn, provides a means of comparing the static and dynamic properties of these materials for a given type of dynamic loading. The rate of application of the dynamic loading was in the range of 25 to 30 microseconds; the wave or pulse length was in the order of 10 inches; and while the exact shape of the wave (linear or curved) cannot be determined, the assumption of a saw-toothed or spiked-wave agrees most closely with the test data, such as the strain time measurements, spall lengths and particle velocities.

Pellet Technique

33. The application of the pellet technique to the measurement of stress induced in cylindrical test specimens of rock and concrete will provide a quantitative value for the critical normal fracture stress (dynamic tensile strength) of these materials under impact loading. However, it is realized that the theoretical assumptions (see paragraph 5) on which this test method is based are not precisely met by the procedures outlined in this report. Therefore, the test method is of a critical nature, requiring care in execution, and with the following limitations:

(1) A number of specimens should be tested over a suitable range of projectile impact velocities to determine within limits the minimum stress at which failure will occur.

(2) The rise time of the pulse created by the projectile impact should be in the order of 25 to 30 microseconds, but not longer.

(3) The test specimen should have a length diameter ratio of not less than 5.

(4) The test specimens used for a given material should be similar and of uniform composition. (If crushing is observed at the impact end of a specimen due to a previous test it should be discarded.)

Direct Measurement of Dynamic Strain.

34. The application of strain gages to measure dynamic strains on the surface of cylindrical test specimens of rock and concrete is more costly and time-consuming than the pellet technique. However, much more information is obtained, and the range of application is greater. Information on the pulse char- ...ics produced by the impact loading are indicated. In the case of the test- ...ribed in this report, it would have been desirable to have three gages ... 120° apart around the periphery of the test specimen at several locations ... of just one or two gages at given stations on the test piece. The strain gages, properly used, provide promise of measuring strains on test specimens under impact loadings producing pulses of slower rise times and on composite test specimens of different materials. The pellet technique would not be applicable for these conditions.

Failure Conditions.

35. Although the purpose of the testing described in this report is to assess the accuracy of the pellet technique for determining the measure of the critical normal fracture stress of rock and concrete, the character of the failure of the fibrous-reinforced concrete is of interest. By the strict definition of spalling, which requires the spall to be completely separated from the parent material, no failure took place for the nylon- or steel-fibre-reinforced concrete specimens under the impact loading. However, for Test Wp3, Wp4, Wp5 and Wp11-4, failure was considered to occur at a stress of about 2800 psi, which produced a crack in the test specimen with no spall separation. Computations, wherein a bond strength of the steel wire and a probable distribution for the steel fibres were assumed, indicated that an impact force producing a stress over three times as large as that which cracked the specimen would be required to cause complete separation of the spall from the parent material. Such an impact force would cause excessive crushing at the impact end of the test specimen, and interfere with the particle velocity measurements. However, the strengthening effect of the fibres might be further assessed by using test specimens with a much smaller fibre content, so that spall separation would be practical from the standpoint of the particle velocity measurement.

PART VIII: CONCLUSIONS

36. On the basis of the test results and analysis presented, the following conclusions are considered warranted:

a. The application of the pellet technique for the measurement of the maximum tensile stress or strain produced in rock or concrete test specimens under the impact loading of a high velocity projectile is practical.

b. The pellet technique provides a means of determining within quantitative limits the dynamic tensile strength (critical normal fracture stress) of cylindrical concrete and rock test specimens (see paragraph 33).

c. The method used in this study for the direct measurement of strain with respect to time provides a record of the strain in both the compressive and tensional phases of the loading pulse.

d. When applying the pellet technique to the measurement of the dynamic tensile strength of other types of materials having a relatively high compressive strength and low tensile strength, direct strain measurements should be made on a few specimens to check the characteristics of the loading pulse and for comparison.

e. The impact device used in this study to load the test specimens produced a shock wave or pulse having a rise time in the range of 20 to 30 microseconds and a wave length in the order of 10 inches.

f. The dynamic tensile strength of the fibre-reinforced concrete is essentially the same as that of the plain concrete (see paragraph 35).

g. The dynamic tensile strength of the plain concrete is over five times its static tensile strength.

h. The dynamic tensile strength of the quartz monzonite rock is about four times its static tensile strength.

i. The pellet technique is applicable only to the measurement of maximum dynamic strains in relatively homogeneous materials. Where shock-absorbing materials are used to reduce the rise time, or the test specimen is a composite of materials, transducers should be used for the direct measurement of dynamic strain.

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Table 1

Average Physical Properties of Materials in Test Specimens

Material	Sp. Gr.	Mass Density, $\frac{lb.-sec^2}{ft^4}$	Seismic Velocity, ft/sec	Youngs Modulus, psi x 10^{-6}		Static Strength, psi	
				Dynamic	Static*	Compressive	Tensile
Aluminum Bar	2.79	5.40	16,000	9.6	9.6	--	33,000
Quartz Monzonite Rock	2.68	5.18	16,900	10.5	10.3	30,000	1,400
Plain Portland Cement Concrete	2.25	4.37	12,600	4.8	4.6	6,200	491**
Nylon Fibre Reinforced Portland Cement Concrete	2.23	4.34	12,500	4.7	3.6	6,100	647**
Steel Fibre Reinforced Portland Cement Concrete	2.31	4.50	12,800	5.1	3.8	8,300	590**
Asbestos Fibre Reinforced Portland Cement Concrete	2.06	4.03	10,850	3.3	--	3,000	--

* Measured in Direct Tension

** Average of Two Tests

Note: All concrete properties shown were obtained at an age of 7-10 days.

Table 2

Summary of Test Results - Aluminum Bar

Test or Shot No.	Projectile Firing Pressure psi	Particle Velocity, fps	Induced Stress psi	Tensile Strain, Micro-inches/in		Variation From Gage Measurement, %
				Pellet Technique	Measured (Strain Gages)	
100	10	8.34	5,000	520	500	+4.0
101	10	8.34	5,000	520	500	+4.0
102	10	8.34	5,000	520	550	-5.4
105	30	30.80	18,500	1920	1900	+1.1

Properties of Aluminum Bar

Length = 12.0 inches
Diameter = 1 3/8 inches
Sp. Gr. = 2.79
Mass Density = 5.40 $\frac{\text{lb - sec}^2}{\text{ft}^4}$
Seismic Velocity = 16,000 ft/sec.
Dynamic Mod. of Elasticity = 9.6 x 10^6 psi

Table 3

Test Conditions, Quartz Monzonite Rock

Test No.	Pressure, psi	Number of Gages	Distance of Gage from Free End, in.	Length of Spall, in.
1B	10	1	4.30	No Spall
1B1	10	1	4.30	No Spall
1B2	10	1	4.30	No Spall
2B	10	1	5.25	No Spall
2B1	14	1	5.25	5.25

Table 4

Summary of Test Results - Quartz Monzonite Rock

Test No.	Size of Specimen, in		Seismic Velocity, ft./sec.	Particle Velocity, ft./sec.	Induced Stress psi	Tensile Strain, Micro-in./in		Variation from Gage Measurement, %	Remarks
	Length	Diam.				Pellet Technique	Measured (Strain Gages)		
1B	8.5	2.4	16,990	5.85	3580	344	337	+2.1	- -
1B1	8.5	2.4	16,990	5.30	3250	318	337	-5.6	- -
1B2	8.5	2.4	16,990	4.68	2850	273	287	-4.9	- -
2B	10.4	2.4	17,500	3.97	2500	227	213	+6.6	- -
2B1	10.4	2.4	17,500	9.27	5840	530	500	+6.0	Failure

Properties of Quartz Monzonite Rock

Sp. Gr. = 2.68

Mass Density = 5.18 $\frac{\text{lb-sec}^2}{\text{ft}^4}$

Avg. Static Mod. of Elasticity (5) = 10.46 x 10^6 psi.
Avg. Dynamic Mod. of Elasticity (5) = 10.3 x 10^6 psi.
Avg. Seismic Velocity (5) = 16,900 ft./sec.

Table 5

Test Conditions, Plain and Fibrous-Reinforced Concrete

Test No.	Pressure psi	Number of Gages	Distance of Gage from Free End, in.	Length of Spall, in.
		Plain Portland Cement Concrete		
Wp2-1	8	2 @ 180°	4.0	None
Wp2-2	10	2 @ 180°	4.0	None
Wp2-3	12	2 @ 180°	4.0	4.5
Wp7-1	8	2 @ 180°	4.5	None
Wp7-2	10	2 @ 180°	4.5	None
Wp7-3	12	2 @ 180°	4.5	5.5
		Nylon Fibre-Reinforced Concrete		
Wp3	20	2 @ 180°	4.5	4.5
Wp4	16	2 @ 180°	4.0	3.0
Wp9-2	10	1	6.0	None
Wp9-3	8	1	6.0	None
		Steel Fibre-Reinforced Concrete		
Wp5	20	2 @ 180°	4.5	3.0 or less
Wp11-2	8	2 @ 180°	4.5	None
Wp11-4	14	2 @ 180°	4.5	5.25
		Asbestos Fibre-Reinforced Concrete		
Wp12-1	10	2 @ 180°	4.5	None
Wp12-2	8	2 @ 180°	4.5	None
Wp12-4	10	2 @ 180°	4.5	None
Wp12-5	10	2 @ 180°	4.5	None

Table 6

Summary of Test Results - Plain and Fibrous-Reinforced Concrete

Type of Specimen*	Test or Shot No.	Mass Density, $\frac{lb\text{-}sec^2}{ft.^4}$	Seismic Velocity, ft/sec.	Particle Velocity, ft/sec.	Induced Stress psi	Tensile Strain by Pellet Technique, Micro-in./in	Remarks
Plain	Wp2-1	4.38	12,450	4.00	1510	320	- -
Portland	Wp2-2	4.38	12,450	6.59	2500	530	- -
Cement	Wp2-3	4.38	12,450	8.49	3210	680	Failure
Concrete	Wp7-1	4.36	12,750	4.59	1770	360	- -
	Wp7-2	4.36	12,750	5.80	2240	460	Discarded**
	Wp7-3	4.36	12,750	10.40	4000	820	Failure
Nylon Fibre-	Wp3	4.31	12,180	15.75	5750	1290	Failure
Reinforced	Wp4	4.31	12,250	13.69	5040	1120	Failure
PCC ***	Wp 9-2	4.36	12,750	8.42	3250	660	- -
(.010 x 1 1/2-in)	Wp9-3	4.36	12,750	3.60	1380	282	- -
Steel Fibre-	Wp5	4.47	12,400	19.54	7500	1570	Failure
Reinforced	Wp11-2	4.54	13,000	-	-	-	- -
PCC ***							
(.017 x 1 1/2-in)	Wp11-4	4.54	13,000	10.40	4260	800	Failure
Asbestos Fibre-	Wp12-1	4.03	10,850	7.20	2180	665	- -
Reinforced	Wp12-2	4.03	10,850	5.39	1640	495	- -
PCC ***	Wp12-4	4.03	10,850	6.00	1820	550	- -
(KB-483-4T)	Wp12-5	4.03	10,850	7.20	2180	665	- -

*Specimens are Cylindrical; Length = 10.25 in., Diam. = 2.0 in.
No. 8 maximum size aggregate used for all specimens
**Improper Fastening of Pellet
***Quantity of Reinforcement used = 1.25% by Volume

"STATIC" STRESS STRAIN CURVE

LOADING RATE: 500 LBS/MIN
BREAK: 0" BELOW TOP GRIP
AGE AT TEST: 9 DAYS
LOAD AT FAILURE: 1630 LBS.

SPECIMEN: PLAIN # 1
8 MAXIMUM AGGREGATE
W/C = 0.5
LENGTH = 10"
DIAMETER = 2"
WATER CURED 7 DAYS

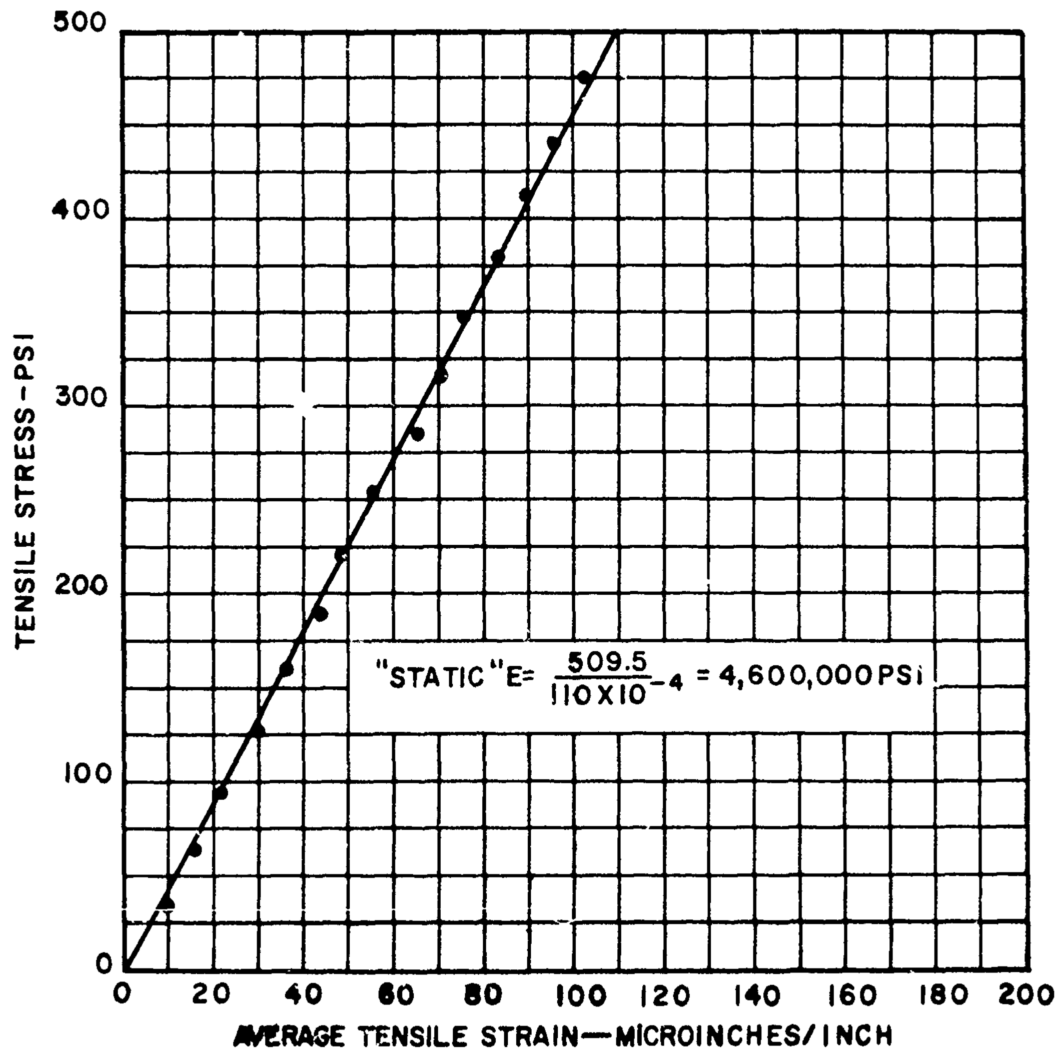


FIGURE 1

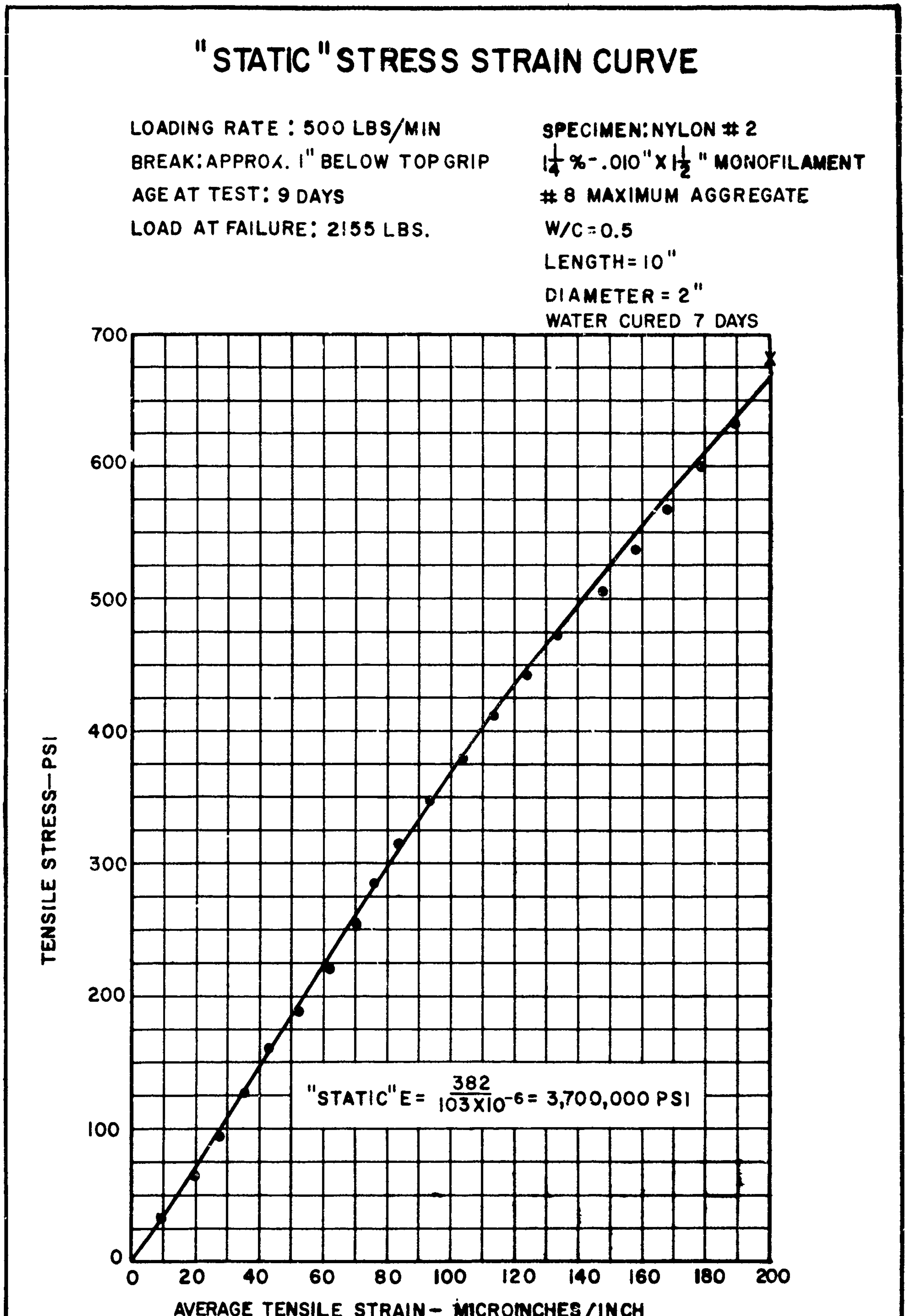

"STATIC" STRESS STRAIN CURVE
LOADING RATE : 500 LBS/MIN
BREAK: APPROX. 1" BELOW TOP GRIP
AGE AT TEST: 9 DAYS
LOAD AT FAILURE: 2155 LBS.
SPECIMEN: NYLON # 2
1¼ %-.010" X 1½ " MONOFILAMENT
8 MAXIMUM AGGREGATE
W/C = 0.5
LENGTH = 10"
DIAMETER = 2"
WATER CURED 7 DAYS
TENSILE STRESS—PSI
0
100
200
300
400
500
600
700
0
20
40
60
80
100
120
140
160
180
200
AVERAGE TENSILE STRAIN— MICROINCHES/INCH
"STATIC" E = $\frac{382}{103 \times 10^{-6}}$ = 3,700,000 PSI

FIGURE 2

"STATIC" STRESS STRAIN CURVE

LOADING RATE: 500 LBS/MIN
BREAK: LOAD FELL OFF TO 70 LBS
AGE AT TEST: 9 DAYS
LOAD AT FAILURE: 1800 LBS

SPECIMEN: STEEL # 1
$1\frac{1}{4}$ %-.017" X $1\frac{1}{4}$" B.P.S.W.
# 8 MAXIMUM AGGREGATE
LENGTH = 10"
DIAMETER = 2"
WATER CURED 7 DAYS

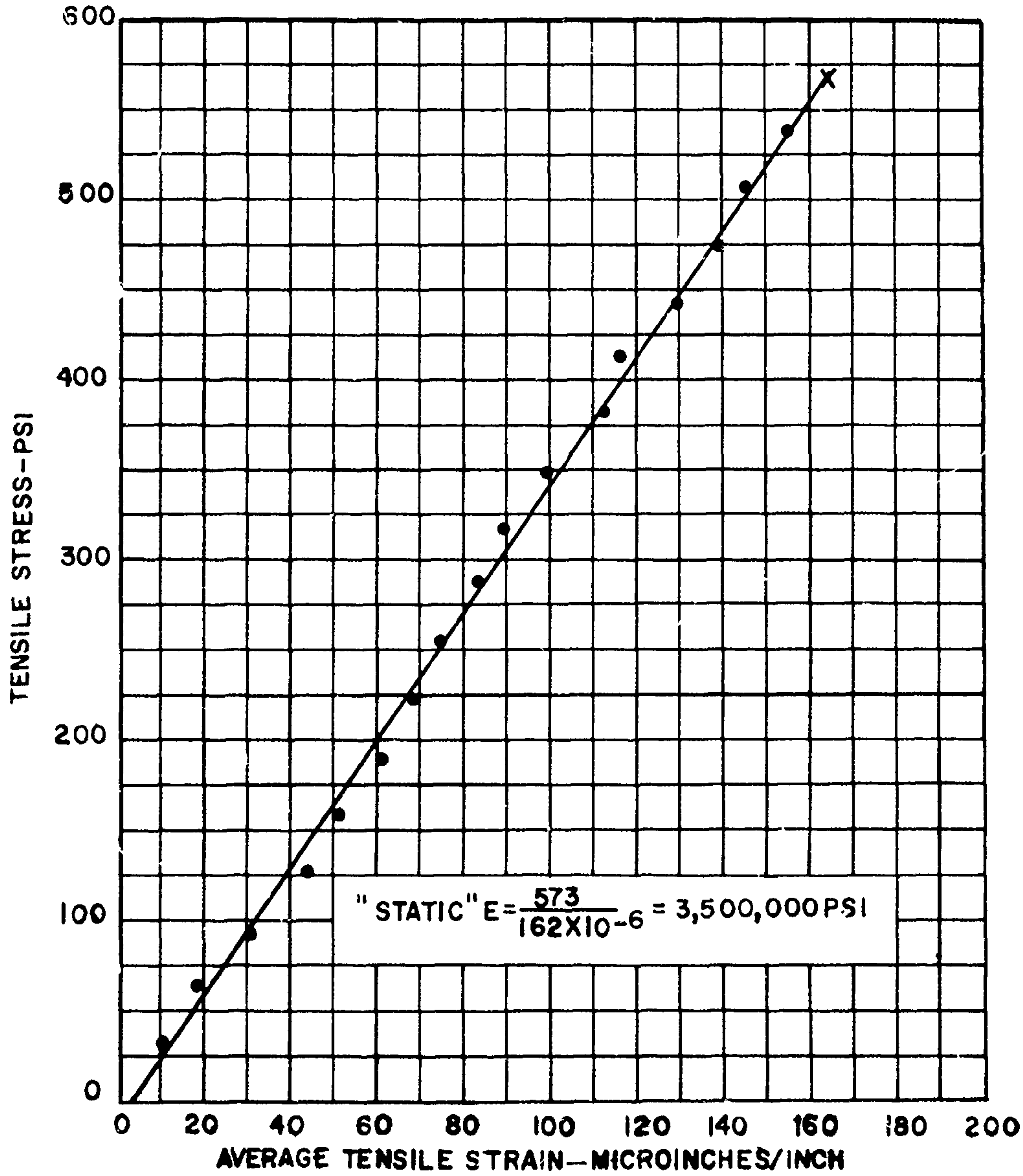


FIGURE 3

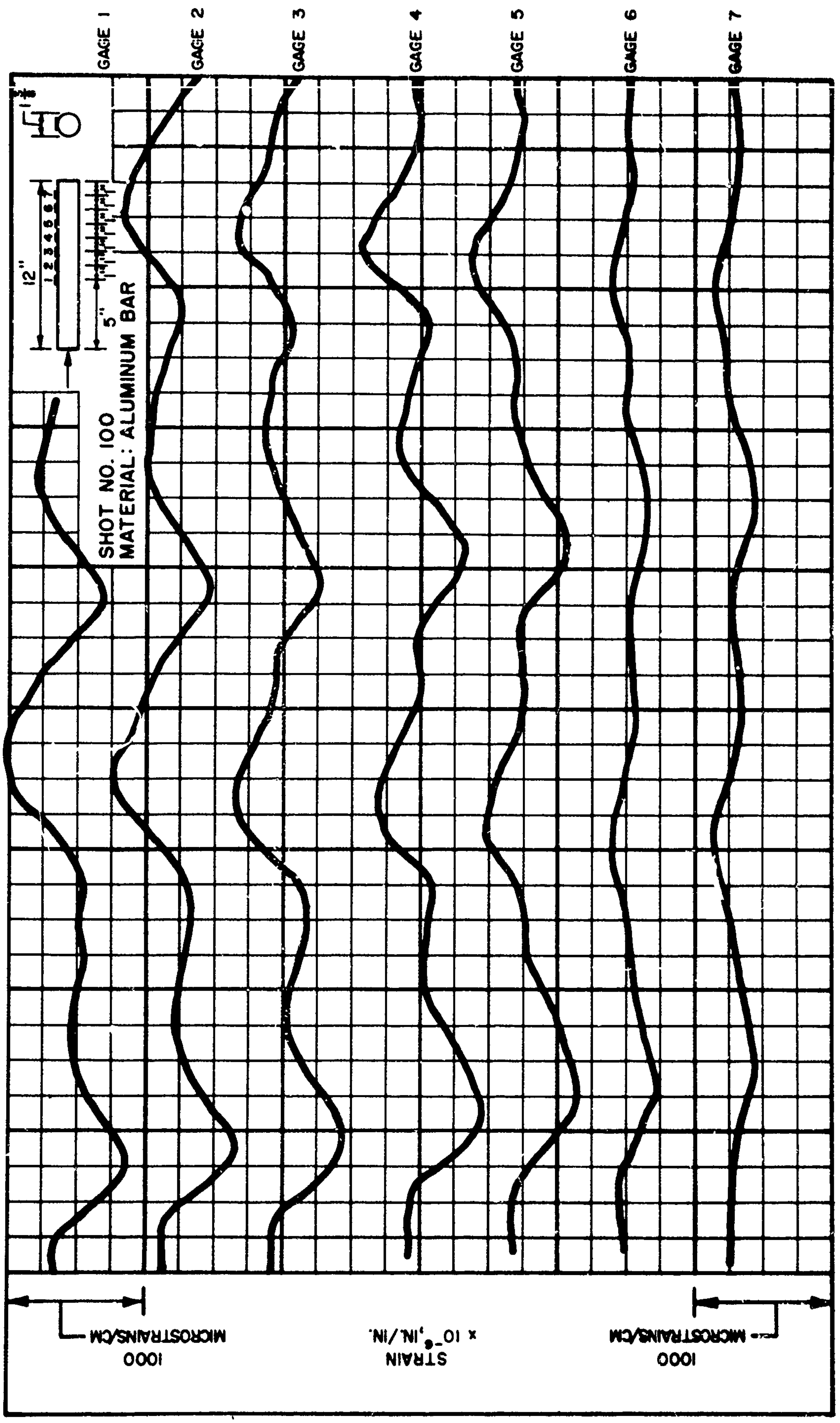

GAGE 1
GAGE 2
GAGE 3
GAGE 4
GAGE 5
GAGE 6
GAGE 7
SHOT NO. 100
MATERIAL: ALUMINUM BAR
12"
5"
1 2 3 4 5 6 7
50
100
150
200
250
300
350
400
TIME (MICROSECONDS)
1000 MICROSTRAINS/CM
STRAIN x 10⁻⁶ IN./IN.
1000 MICROSTRAINS/CM

FIGURE 4

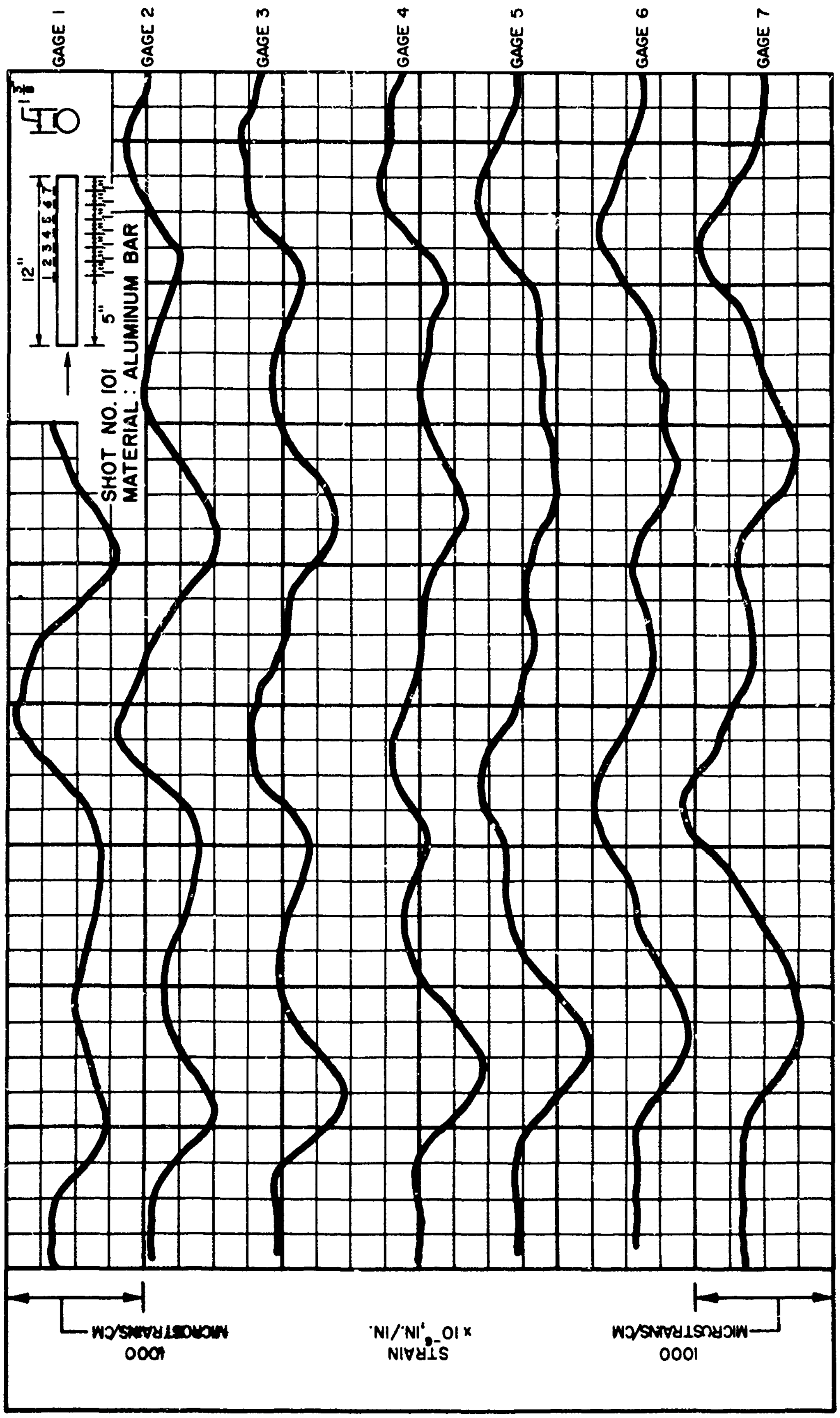

GAGE 1
GAGE 2
GAGE 3
GAGE 4
GAGE 5
GAGE 6
GAGE 7
SHOT NO. 101
MATERIAL : ALUMINUM BAR
12"
5"
1 2 3 4 5 6 7
50
100
150
200
250
300
350
400
TIME (MICROSECONDS)
1000 MICROSTRAINS/CM
STRAIN x 10⁻⁶ IN./IN.
1000 MICROSTRAINS/CM

FIGURE 5

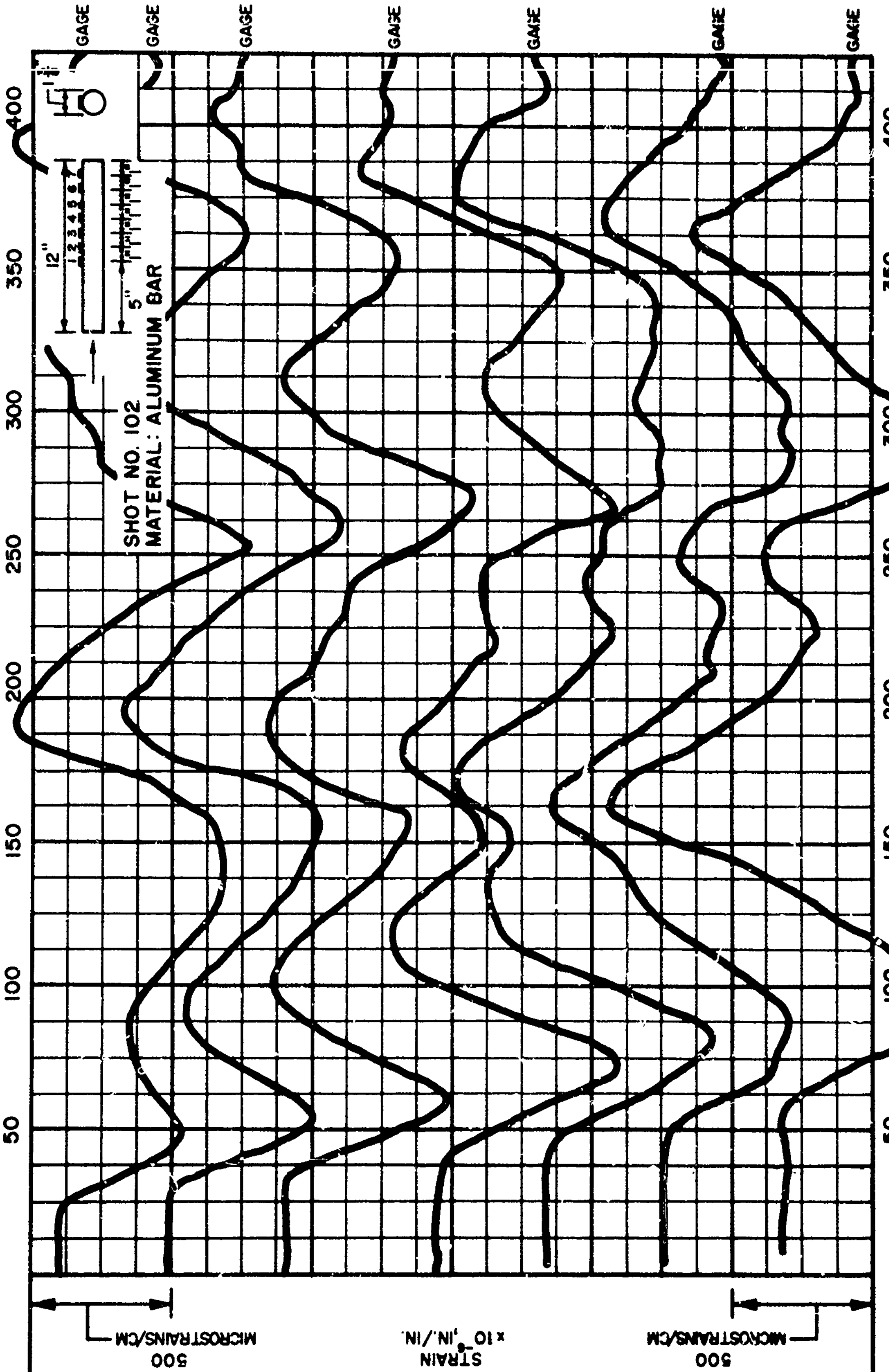

GAGE 1
GAGE 2
GAGE 3
GAGE 4
GAGE 5
GAGE 6
GAGE 7
SHOT NO. 102
MATERIAL: ALUMINUM BAR
12"
5"
TIME (MICROSECONDS)
500 MICROSTRAINS/CM
STRAIN x 10^-6 IN./IN.
500 MICROSTRAINS/CM

FIGURE 6

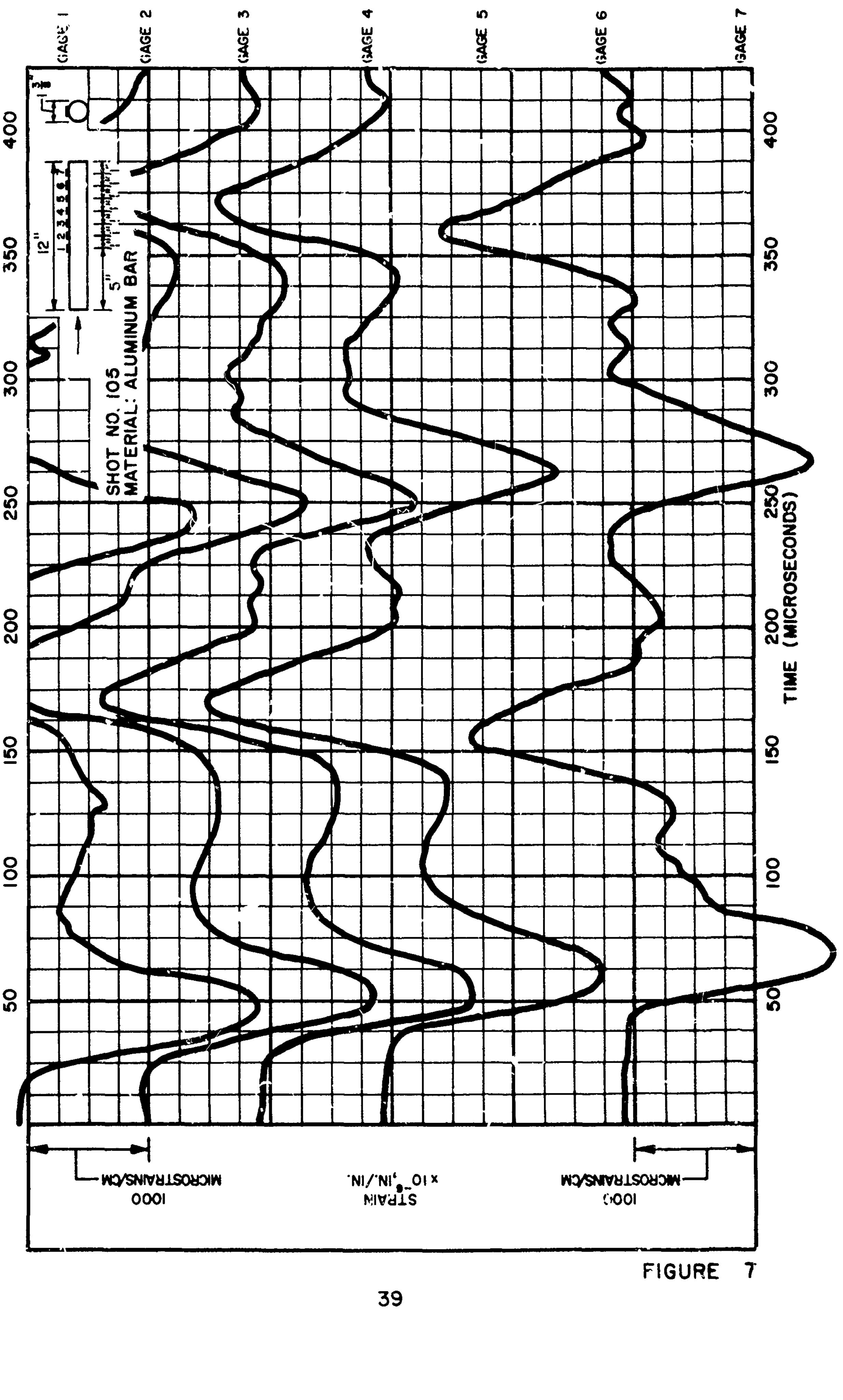

GAGE 1
GAGE 2
GAGE 3
GAGE 4
GAGE 5
GAGE 6
GAGE 7
SHOT NO. 105
MATERIAL: ALUMINUM BAR
12"
5"
1 2 3 4 5 6 7
50
100
150
200
250
300
350
400
TIME (MICROSECONDS)
1000 MICROSTRAINS/CM
STRAIN x10⁻⁶ IN./IN.
1000 MICROSTRAINS/CM

FIGURE 7

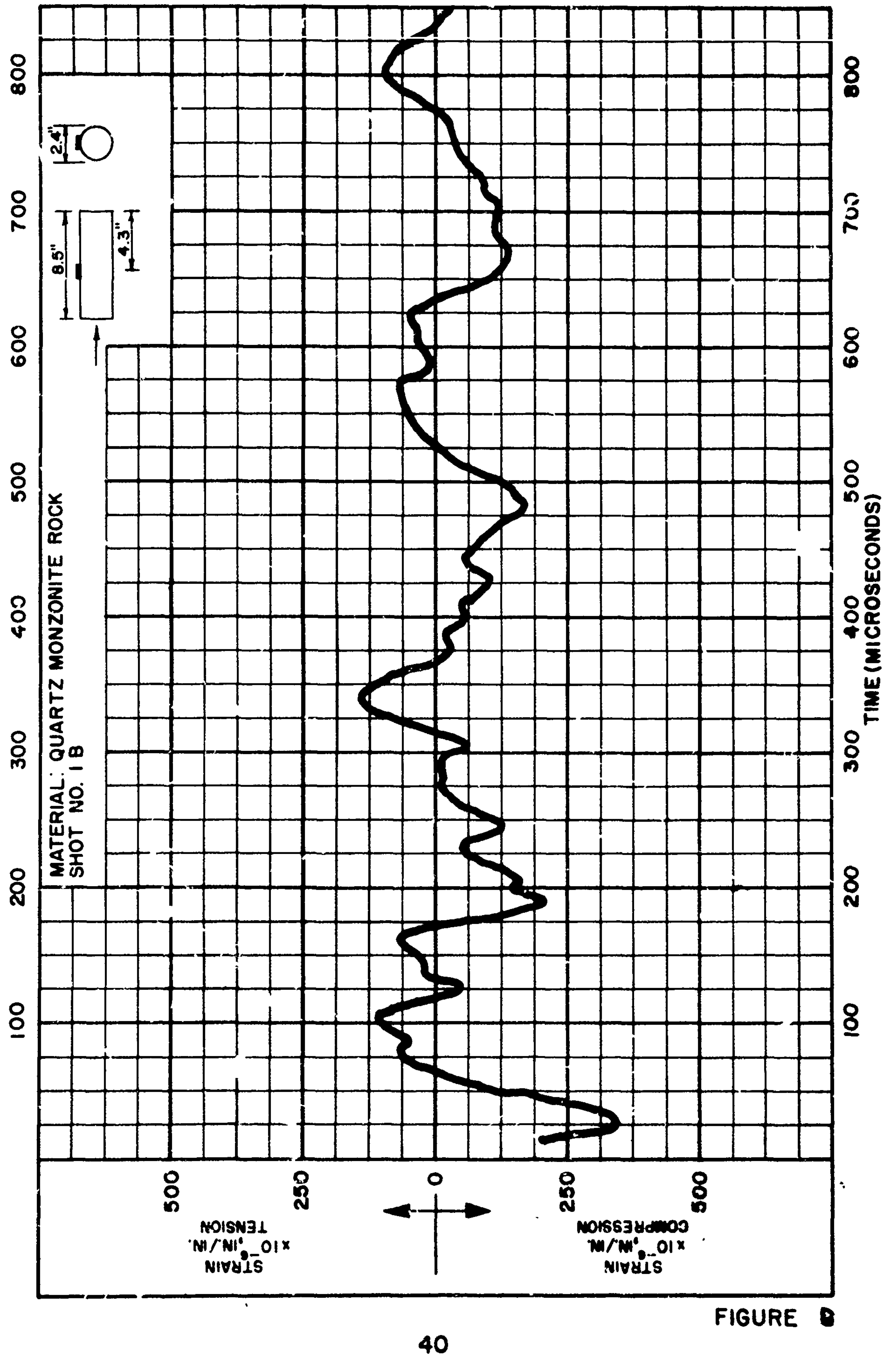

MATERIAL: QUARTZ MONZONITE ROCK
SHOT NO. 1 B
8.5"
4.3"
2.4"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
STRAIN
x10⁻⁶ IN./IN.
TENSION
STRAIN
x10⁻⁶ IN./IN.
COMPRESSION
500
250
0
250
500

FIGURE 8

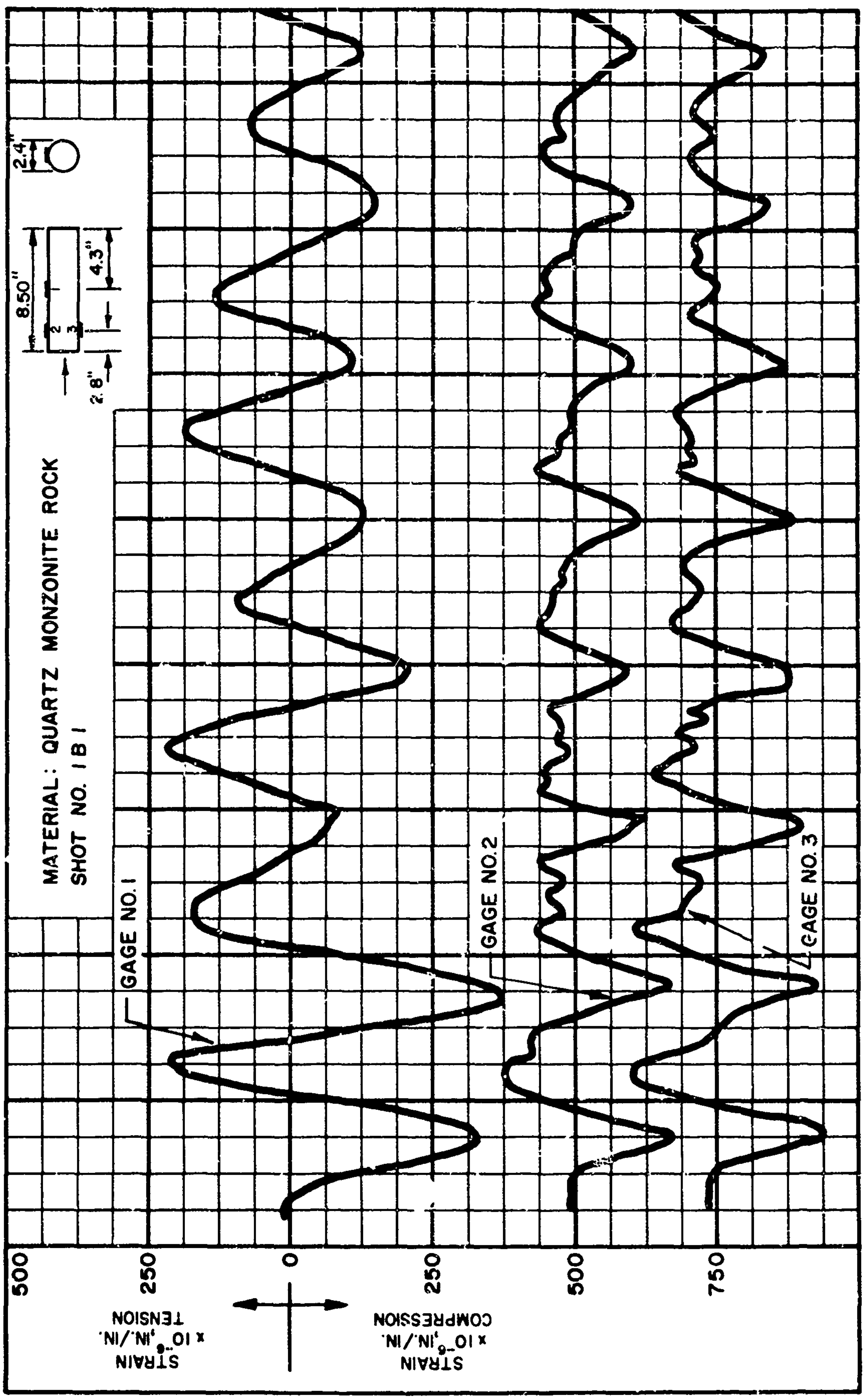
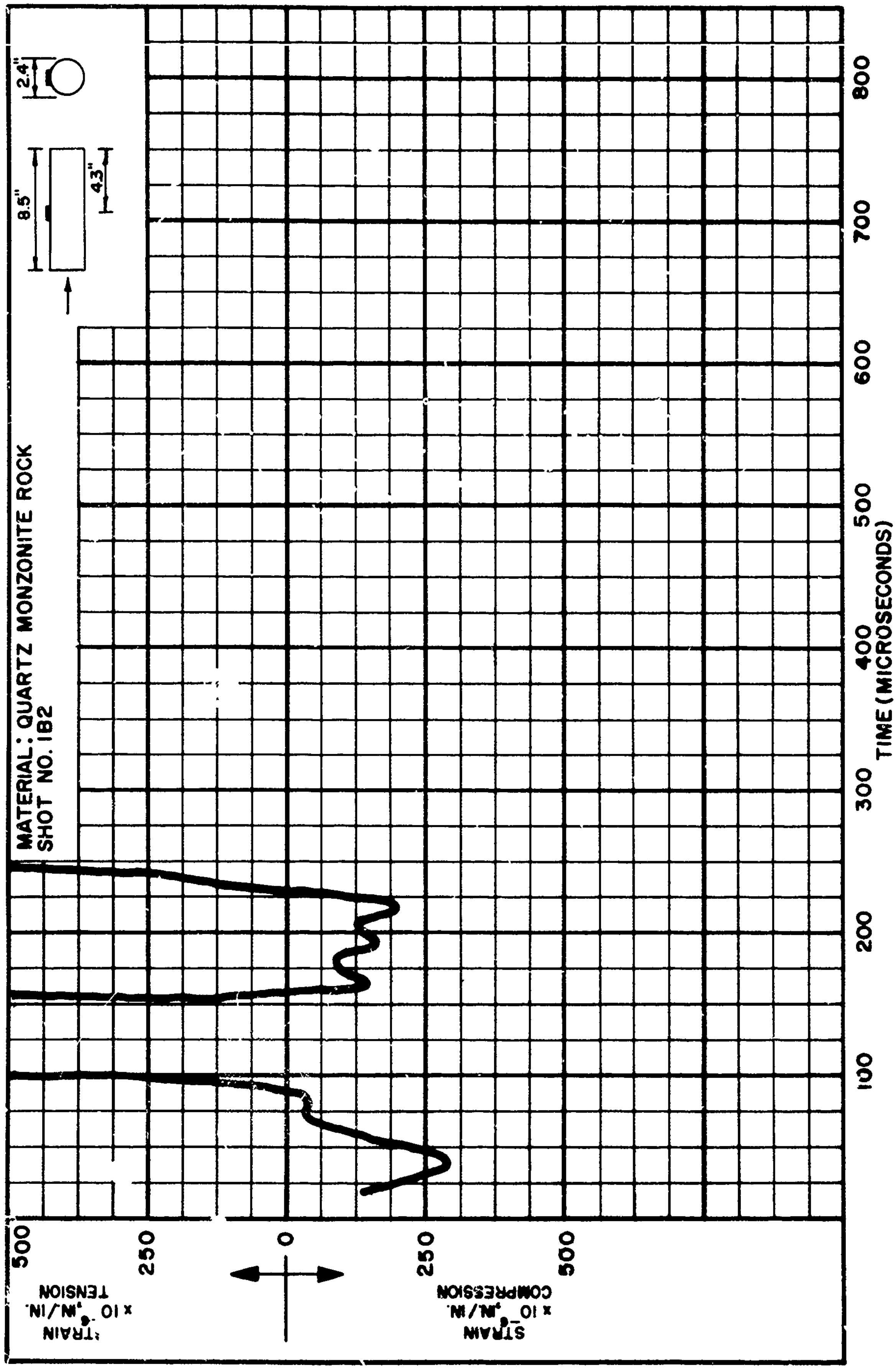

MATERIAL: QUARTZ MONZONITE ROCK
SHOT NO. 1B1
GAGE NO.1
GAGE NO.2
GAGE NO.3
8.50"
4.3"
2.8"
2.4"
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
500
250
0
250
500
750
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)

FIGURE 9



MATERIAL: QUARTZ MONZONITE ROCK
SHOT NO. IB2
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
500
250
0
250
500
8.5"
4.3"
2.4"

FIGURE 10

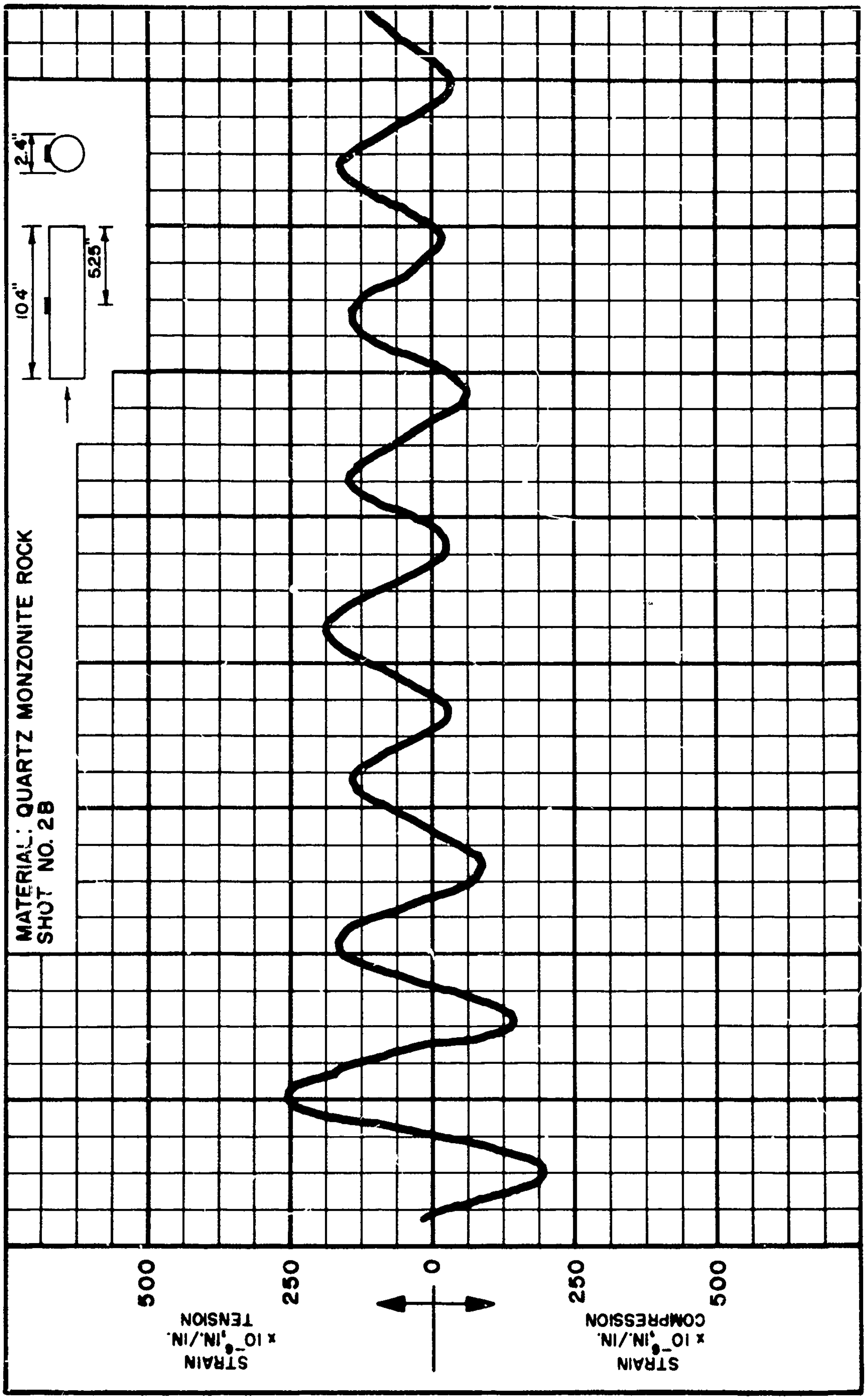

MATERIAL: QUARTZ MONZONITE ROCK
SHOT NO. 2B
10.4"
5.25"
2.4"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
500
250
0
250
500
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION

FIGURE 11

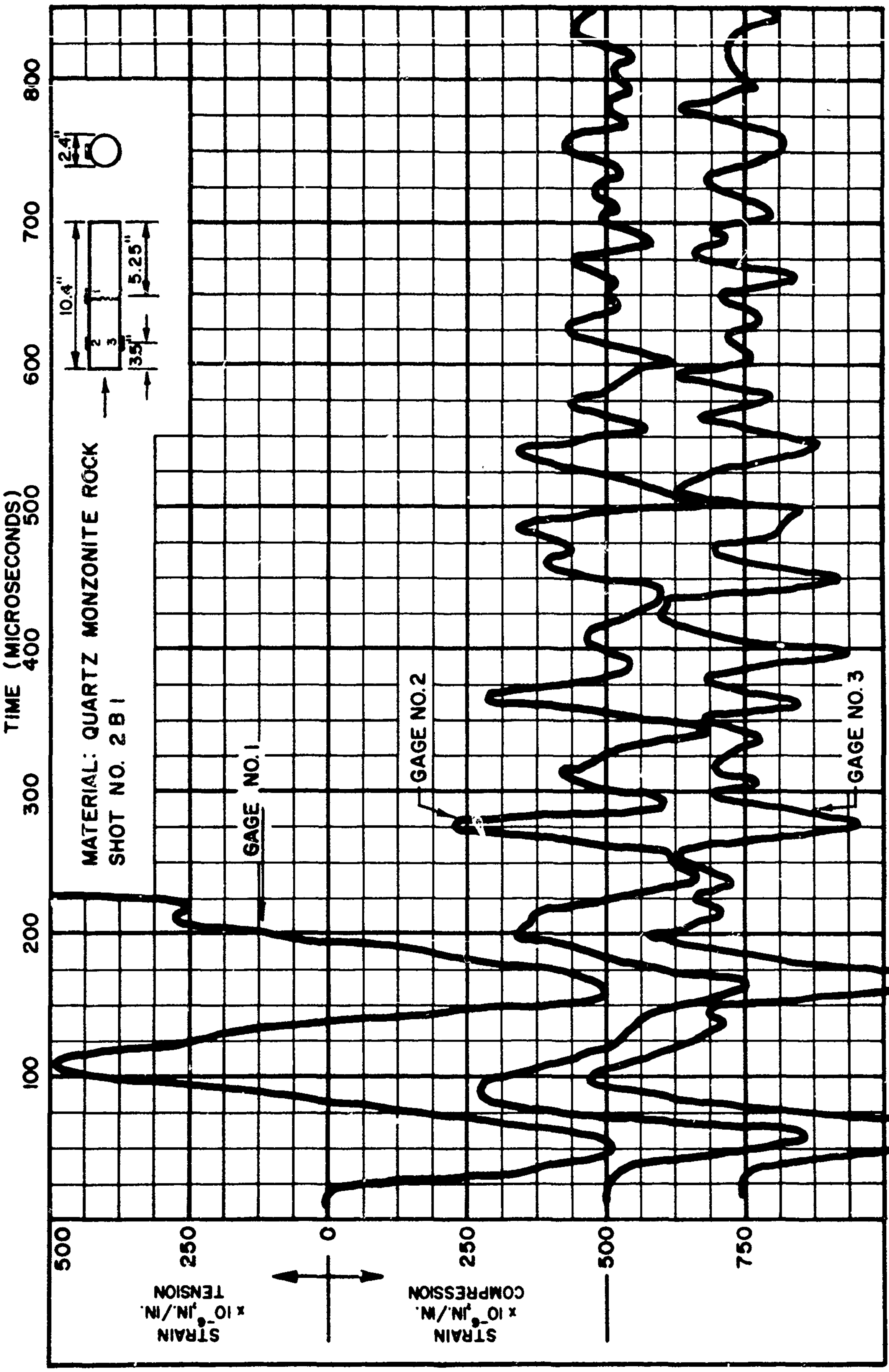

TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
MATERIAL: QUARTZ MONZONITE ROCK
SHOT NO. 2 B 1
10.4"
5.25"
3.5"
2.4"
GAGE NO. 1
GAGE NO. 2
GAGE NO. 3
500
250
0
250
500
750
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION

FIGURE 12

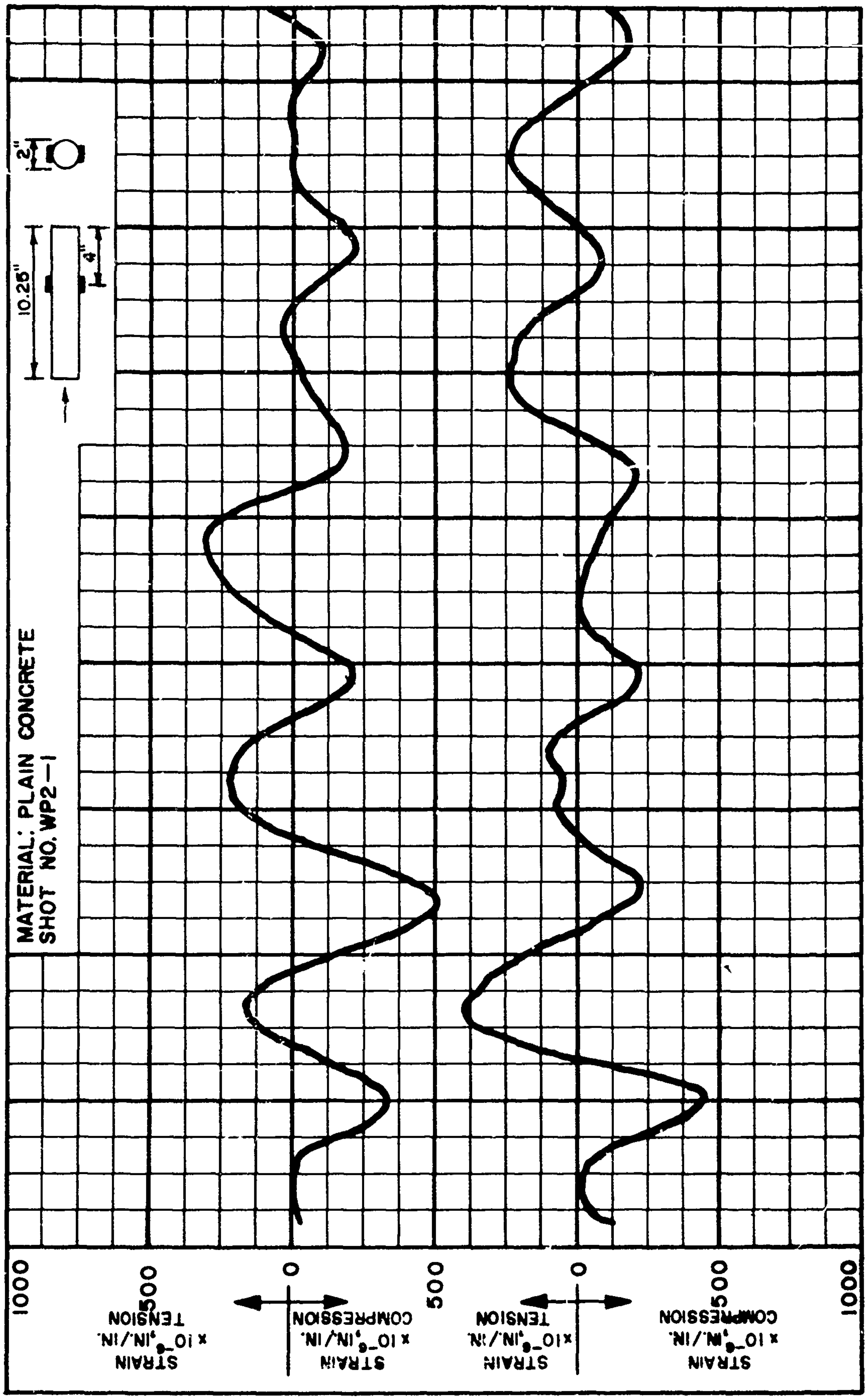

MATERIAL: PLAIN CONCRETE
SHOT NO. WP2—1
10.25"
4"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
1000
500
0
500
0
500
1000
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
STRAIN x10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION

FIGURE 13

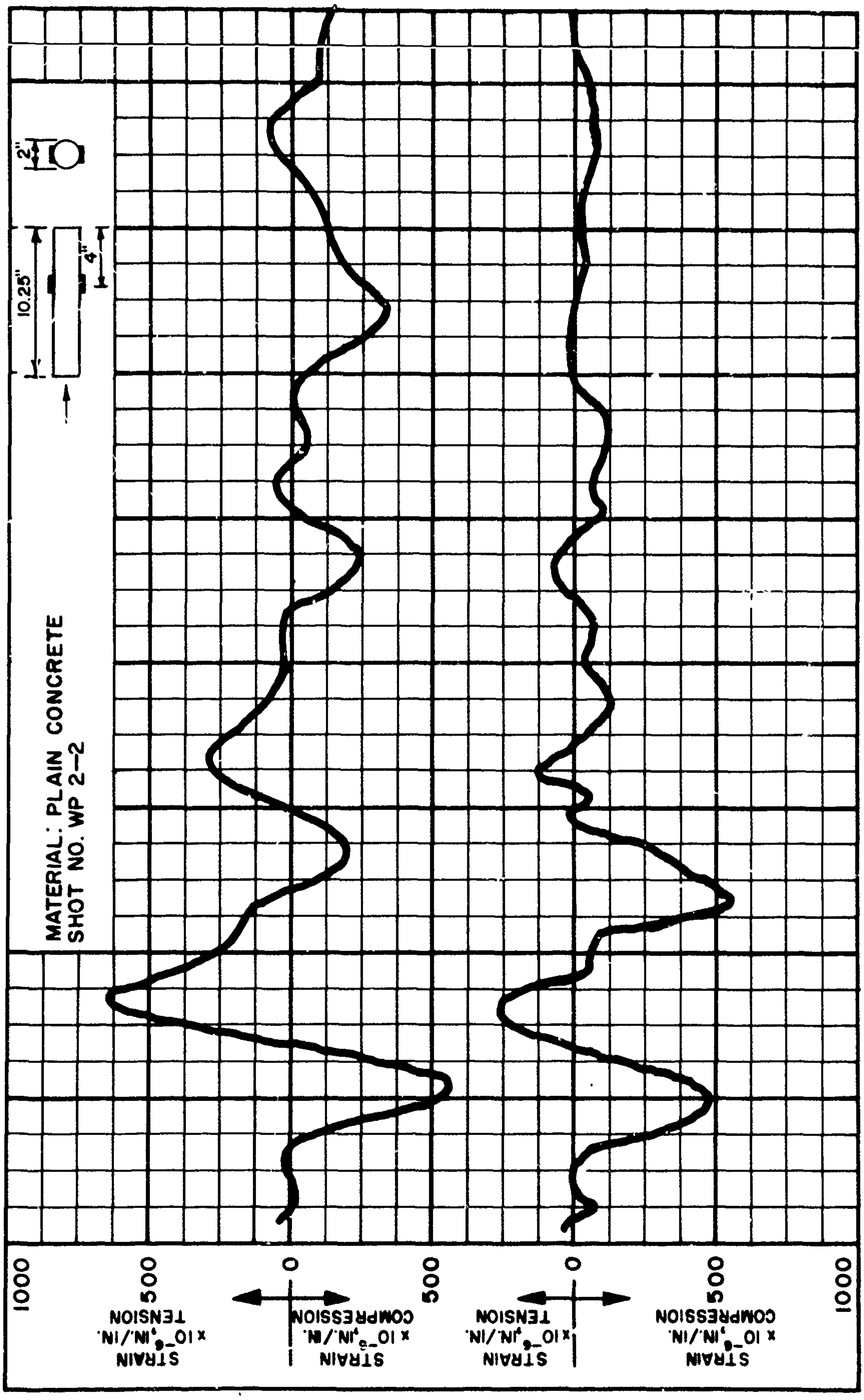
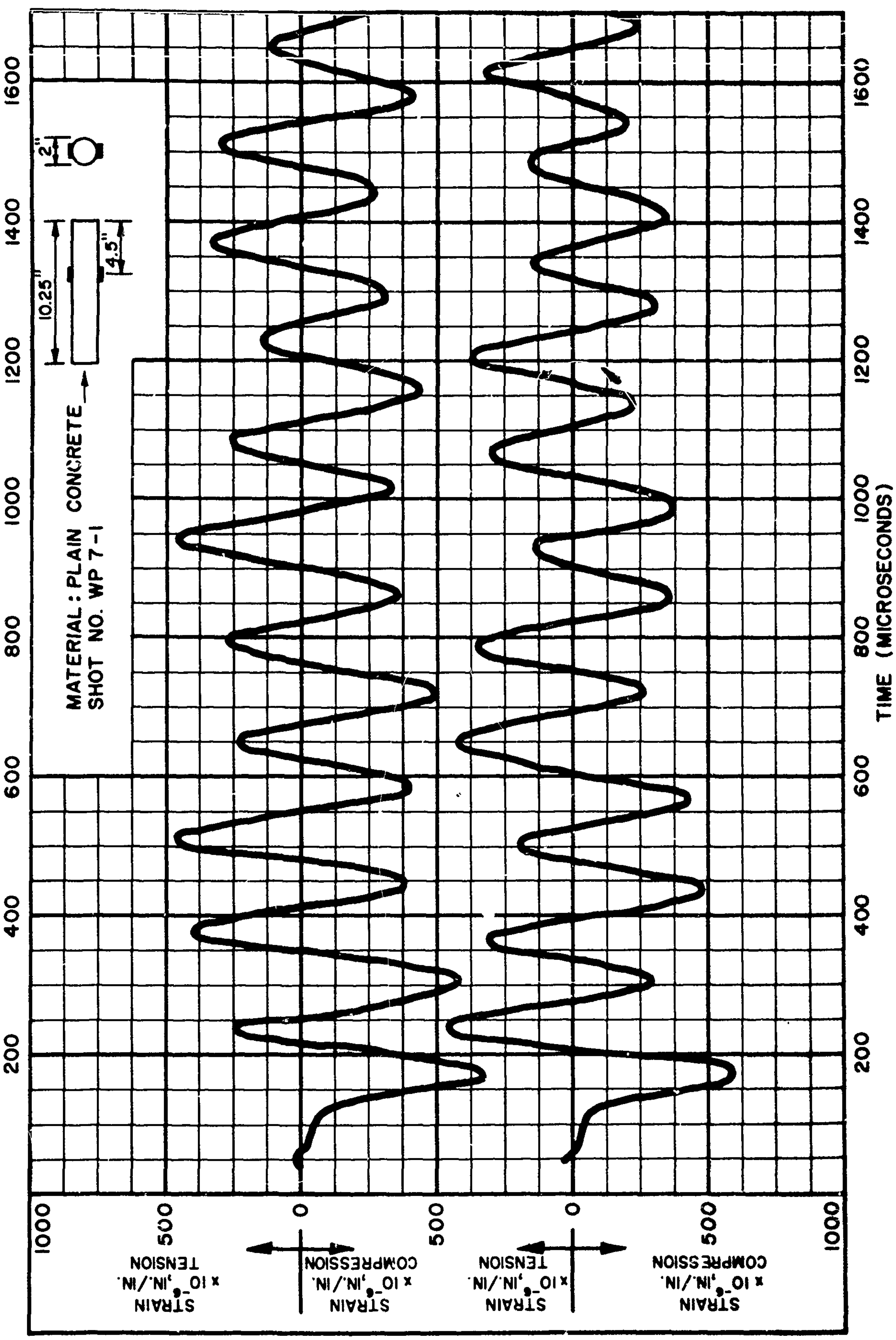

MATERIAL: PLAIN CONCRETE
SHOT NO. WP 2-2
10.25"
4"
2"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
1000
500
0

FIGURE 14



MATERIAL : PLAIN CONCRETE
SHOT NO. WP 7-1
10.25"
4.5"
2"
TIME (MICROSECONDS)
200
400
600
800
1000
1200
1400
1600
1000
500
0
500
1000
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION

FIGURE 15

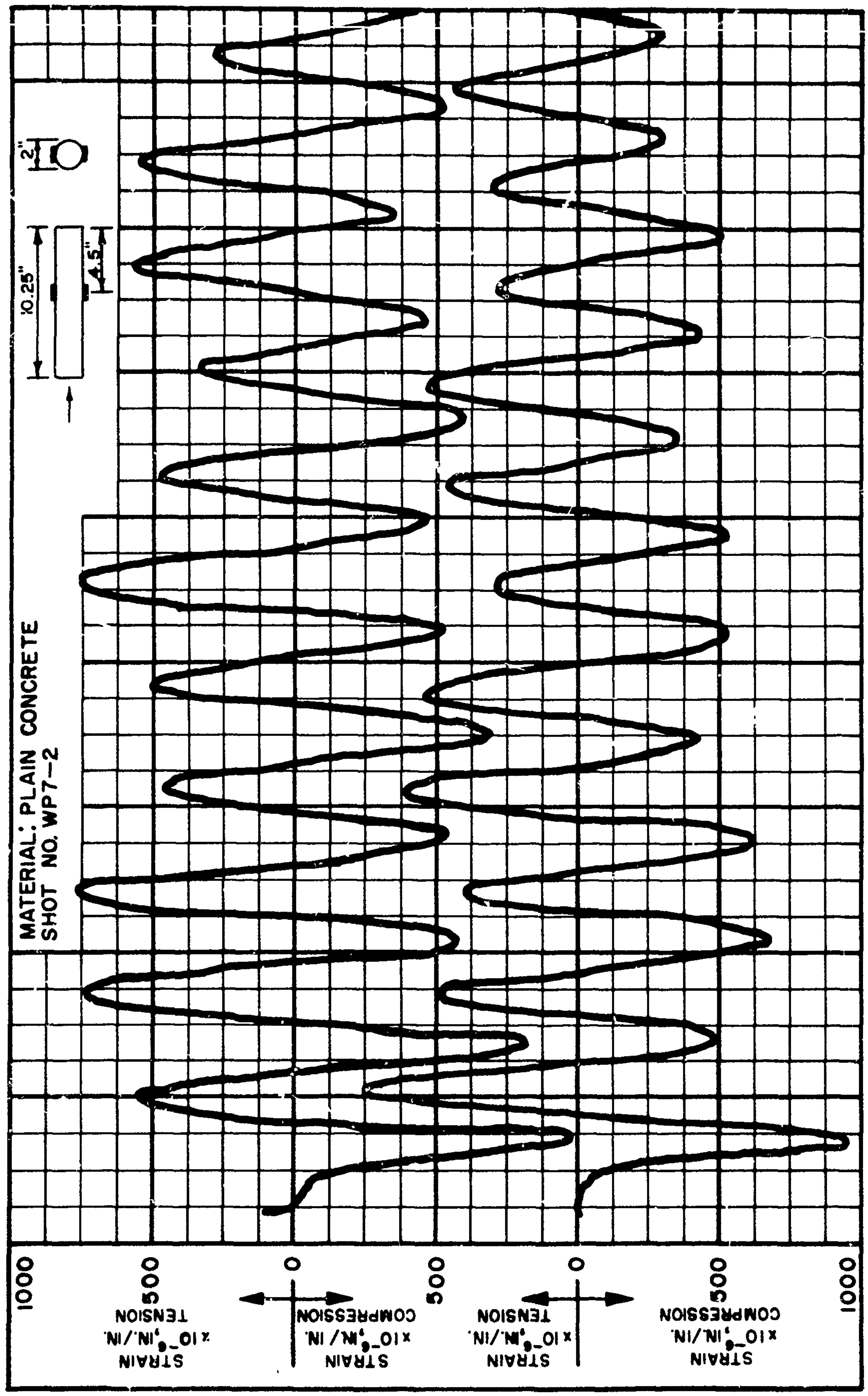

MATERIAL: PLAIN CONCRETE
SHOT NO. WP7-2
10.25"
4.5"
2"
200
400
600
800
1000
1200
1400
1600
TIME (MICROSECONDS)
1000
500
0
500
0
500
1000
STRAIN x10^-6 IN./IN. TENSION
STRAIN x10^-6 IN./IN. COMPRESSION
STRAIN x10^-6 IN./IN. TENSION
STRAIN x10^-6 IN./IN. COMPRESSION

FIGURE 16

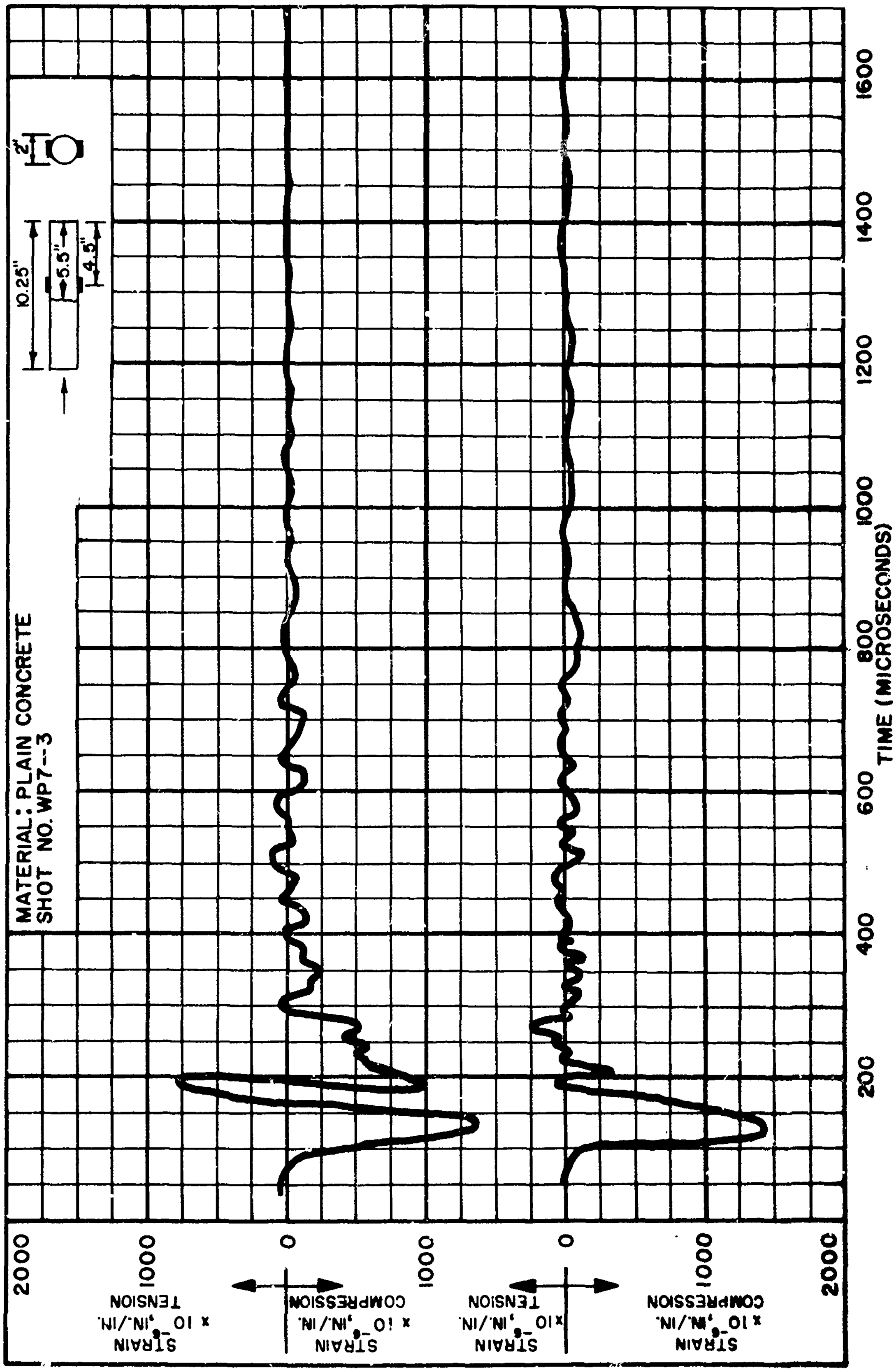
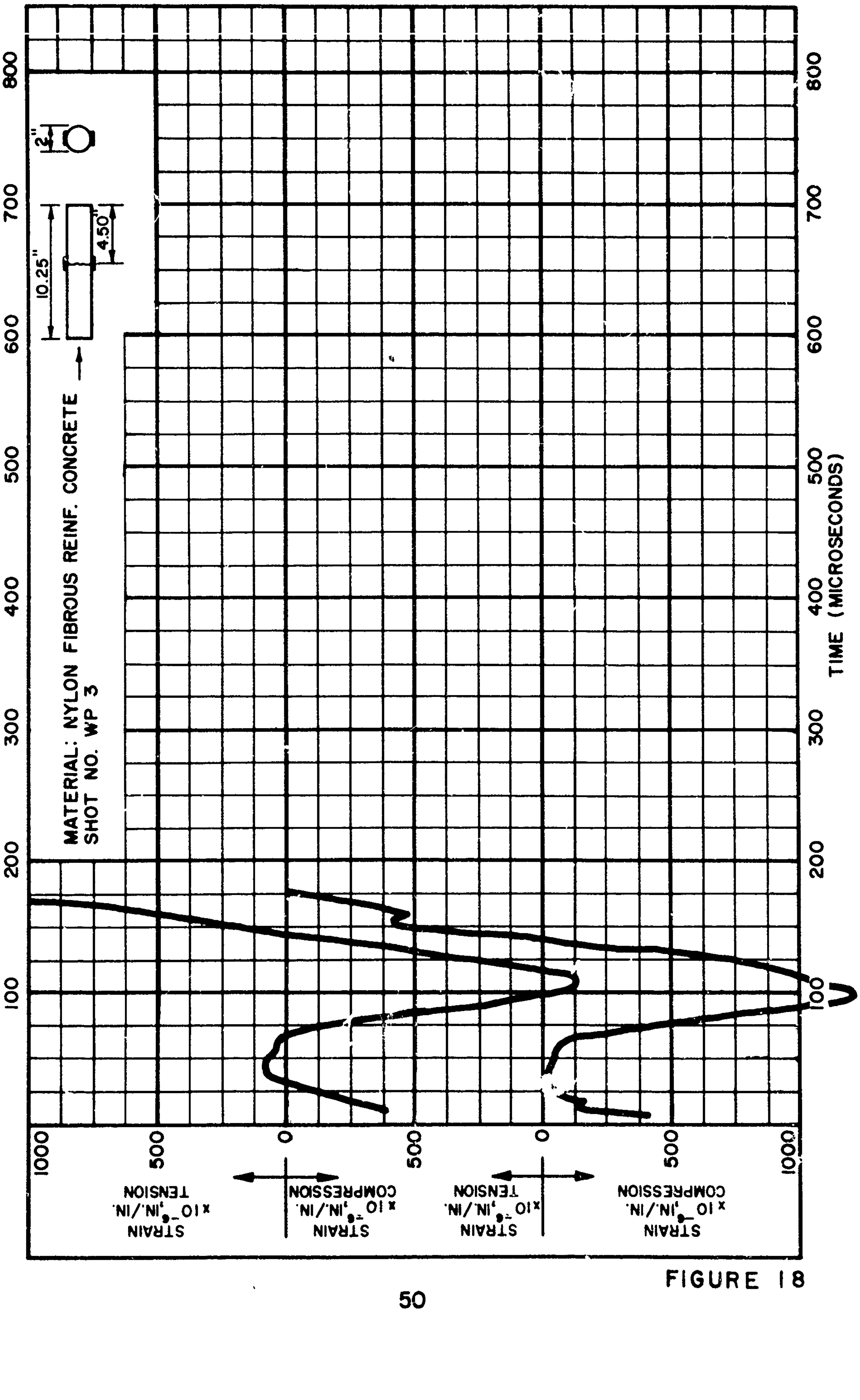

MATERIAL: PLAIN CONCRETE
SHOT NO. WP7-3
10.25"
5.5"
4.5"
2"
TIME (MICROSECONDS)
200
400
600
800
1000
1200
1400
1600
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
2000
1000
0
1000
2000

FIGURE 17



MATERIAL: NYLON FIBROUS REINF. CONCRETE
SHOT NO. WP 3
10.25"
4.50"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
STRAIN x 10⁻⁶ IN./IN. TENSION
STRAIN x 10⁻⁶ IN./IN. COMPRESSION
1000
500
0
500
0
500
1000

FIGURE 18

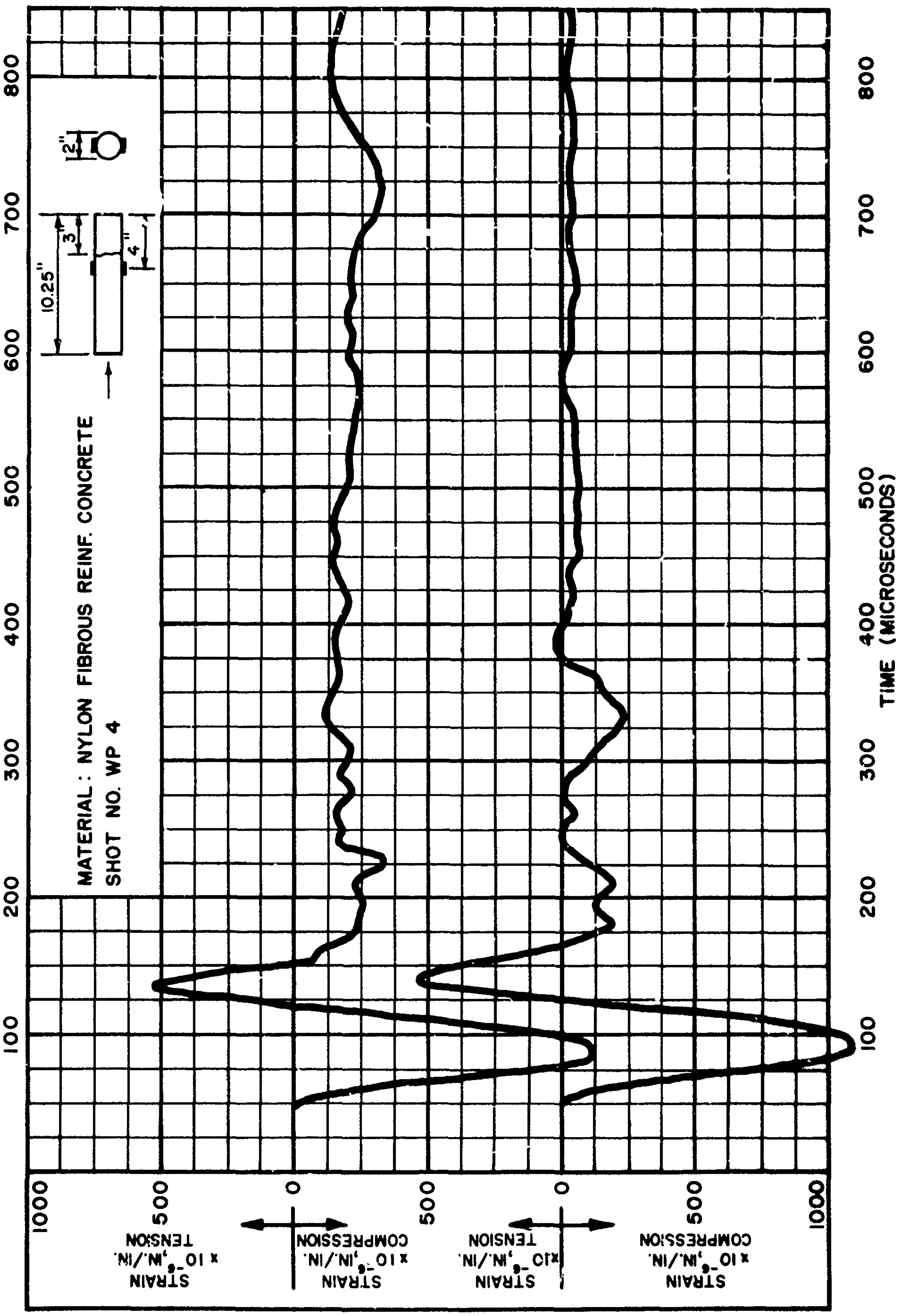

MATERIAL : NYLON FIBROUS REINF. CONCRETE
SHOT NO. WP 4
10.25"
3"
4"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
1000
500
0
STRAIN x 10-6 IN./IN. TENSION
STRAIN x 10-6 IN./IN. COMPRESSION

FIGURE 19

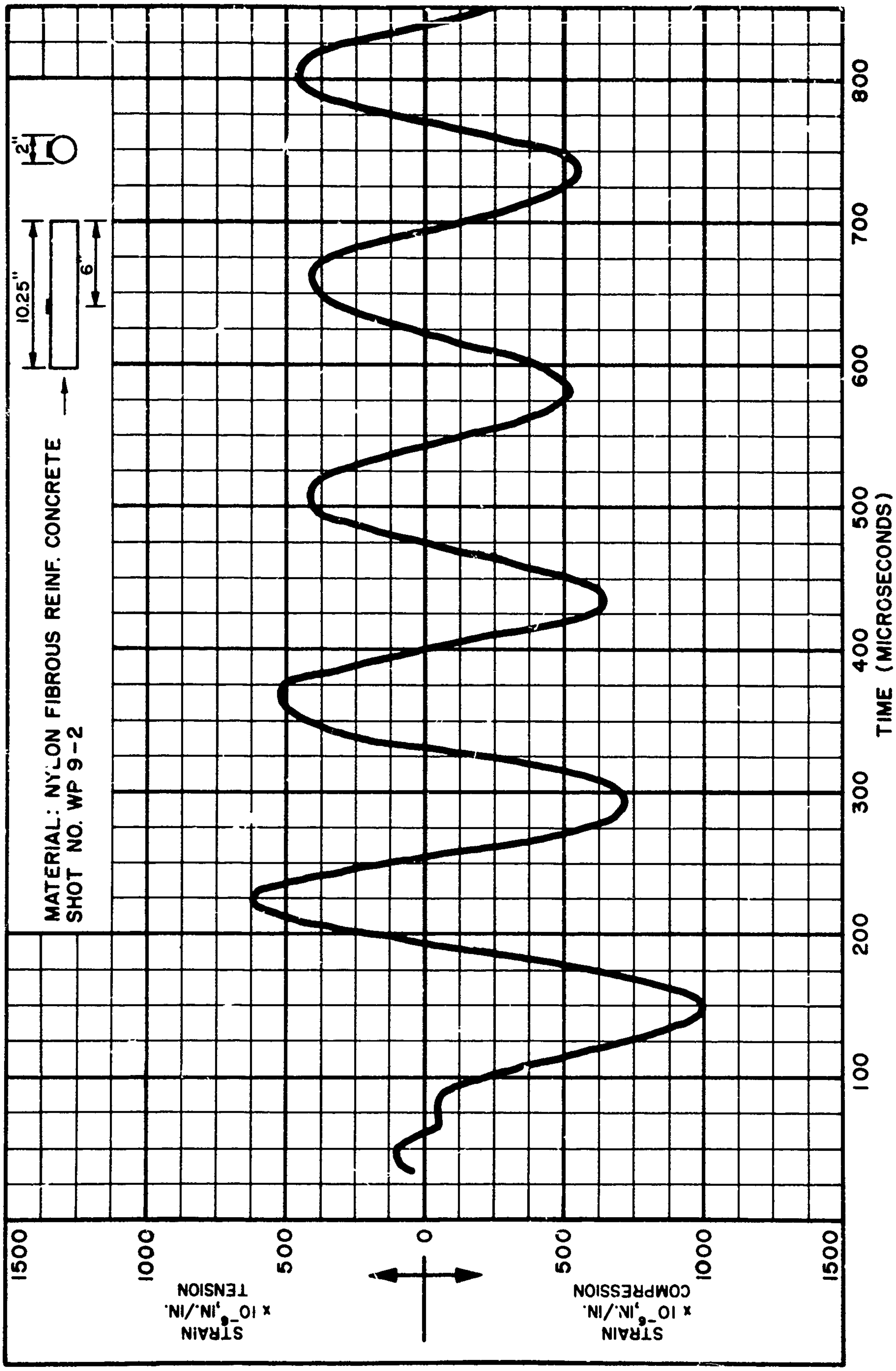

MATERIAL: NYLON FIBROUS REINF. CONCRETE
SHOT NO. WP 9-2
10.25"
6"
2"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
1500
1000
500
0
500
1000
1500
STRAIN
x 10^-6 IN./IN.
TENSION
STRAIN
x 10^-6 IN./IN.
COMPRESSION

FIGURE 20

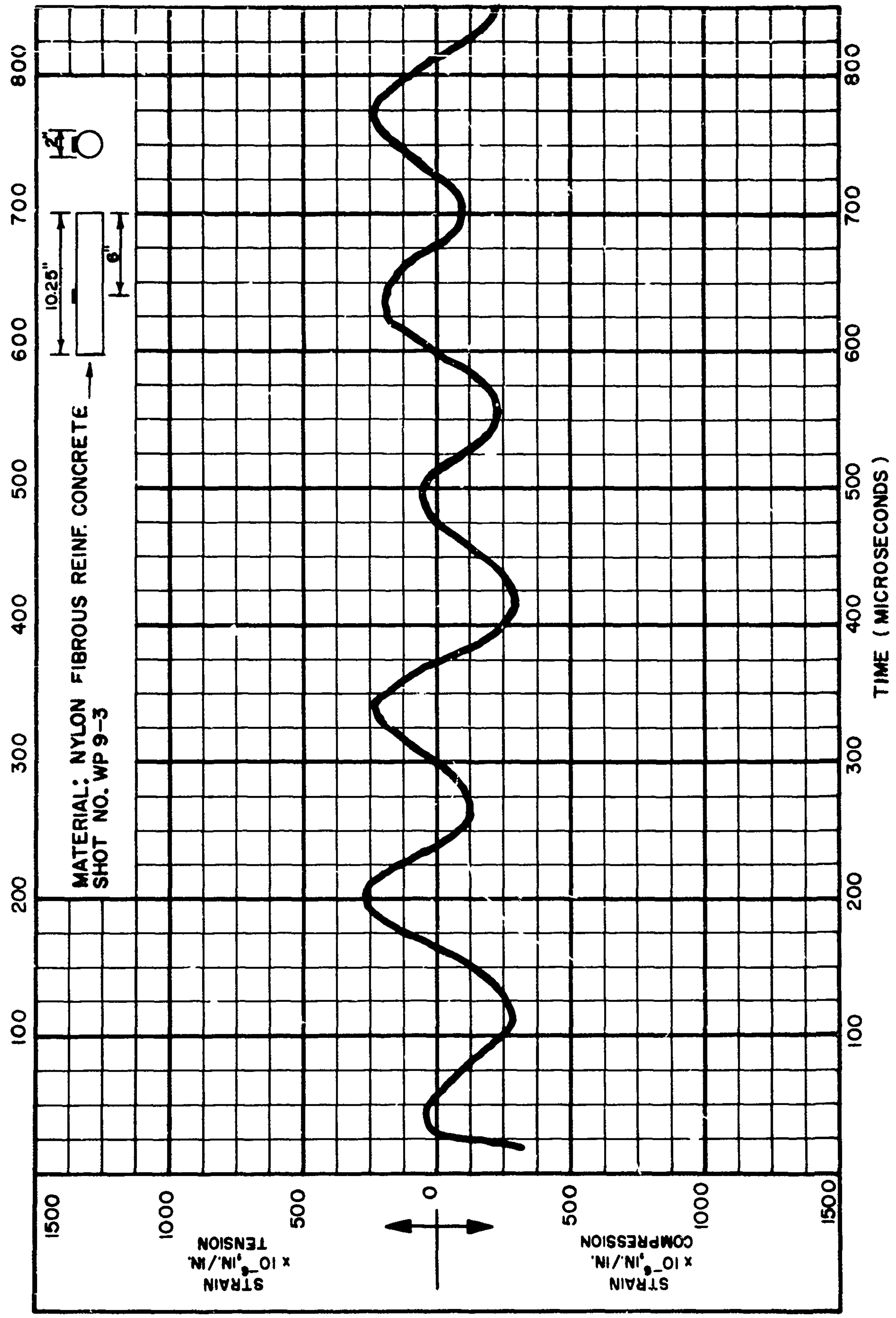

MATERIAL: NYLON FIBROUS REINF. CONCRETE
SHOT NO. WP 9-3
10.25"
6"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
1500
1000
500
0

FIGURE 21

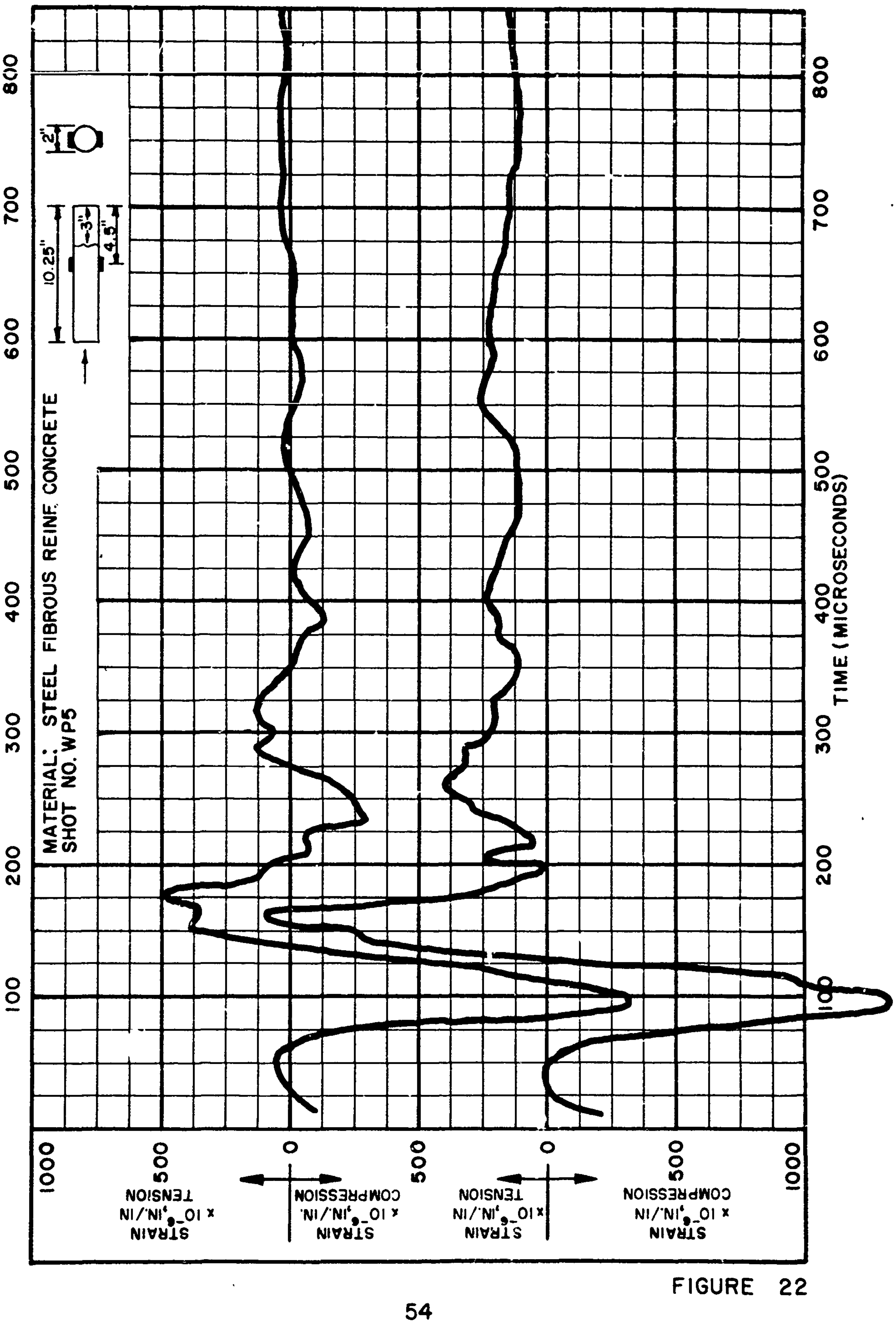

MATERIAL: STEEL FIBROUS REINF. CONCRETE
SHOT NO. WP5
10.25"
3"
4.5"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
1000
500
0
500
0
500
1000
STRAIN
x 10⁻⁶ IN./IN
TENSION
STRAIN
x 10⁻⁶ IN./IN.
COMPRESSION
STRAIN
x 10⁻⁶ IN./IN
TENSION
STRAIN
x 10⁻⁶ IN./IN
COMPRESSION

FIGURE 22

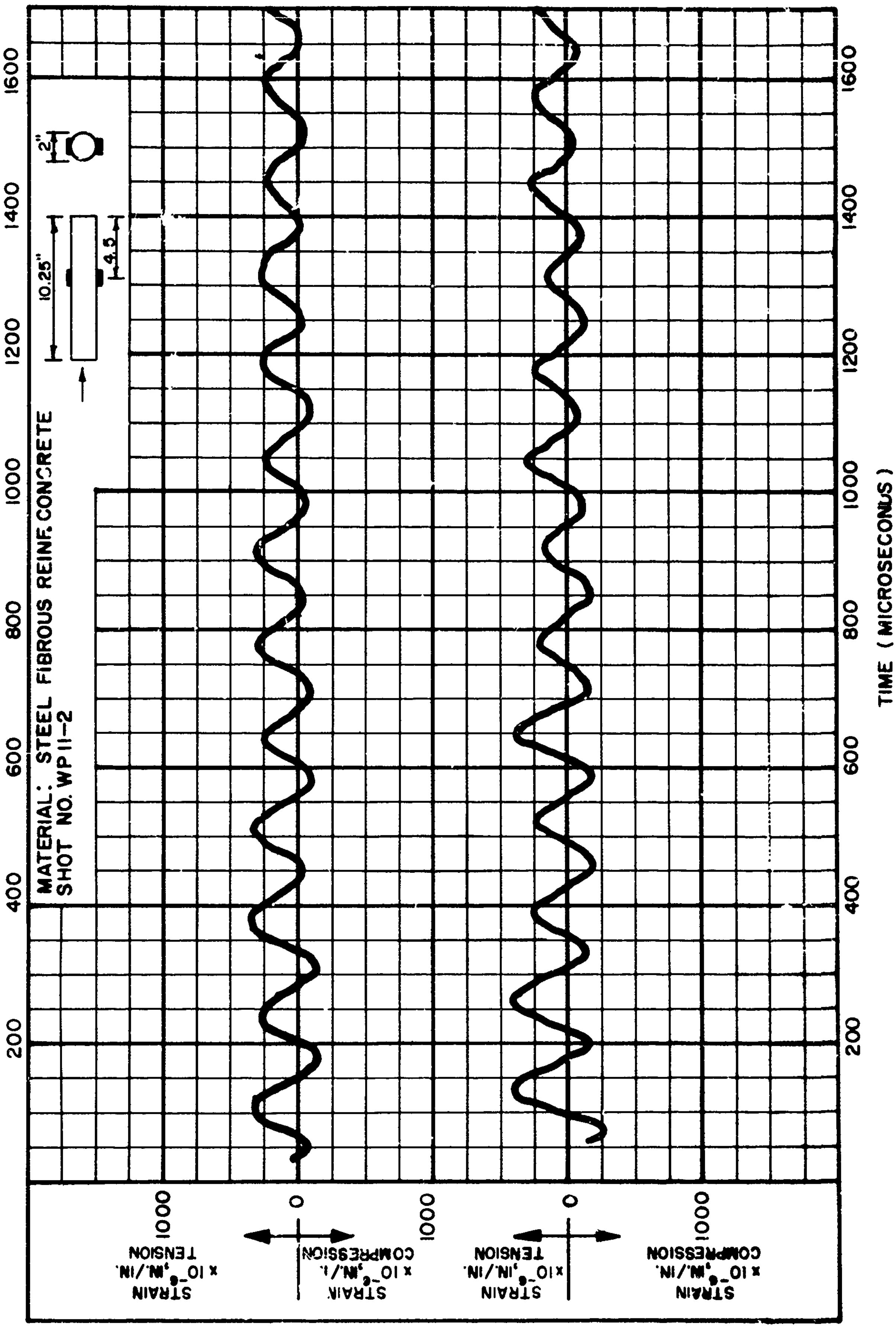

MATERIAL: STEEL FIBROUS REINF. CONCRETE
SHOT NO. WP 11-2
10.25"
4.5
2"
200
400
600
800
1000
1200
1400
1600
TIME (MICROSECONDS)
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
1000
0

FIGURE 23

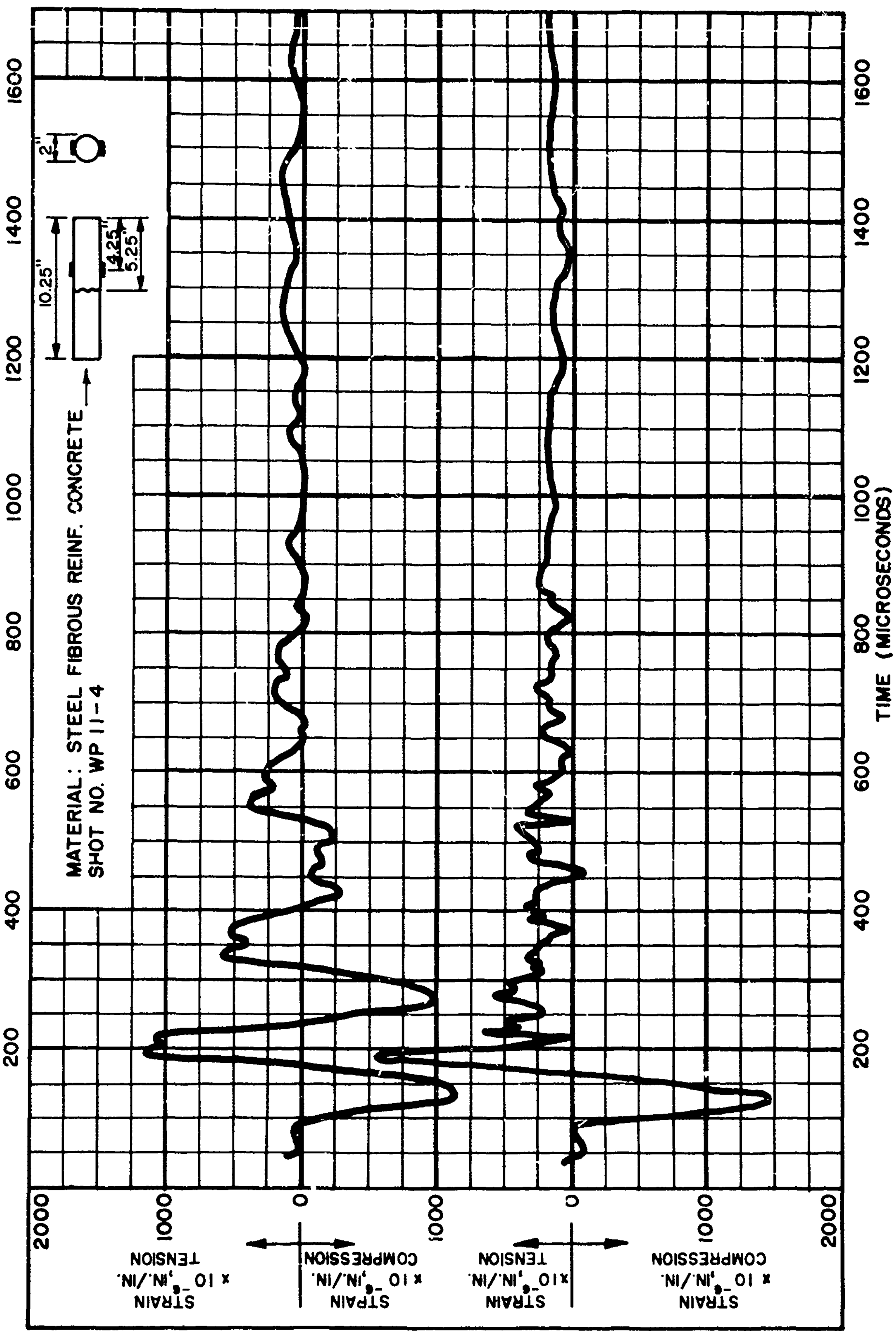

MATERIAL: STEEL FIBROUS REINF. CONCRETE
SHOT NO. WP 11-4
10.25"
4.25"
5.25"
2"
0
200
400
600
800
1000
1200
1400
1600
TIME (MICROSECONDS)
2000
1000
0
1000
0
1000
2000
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION

FIGURE 24

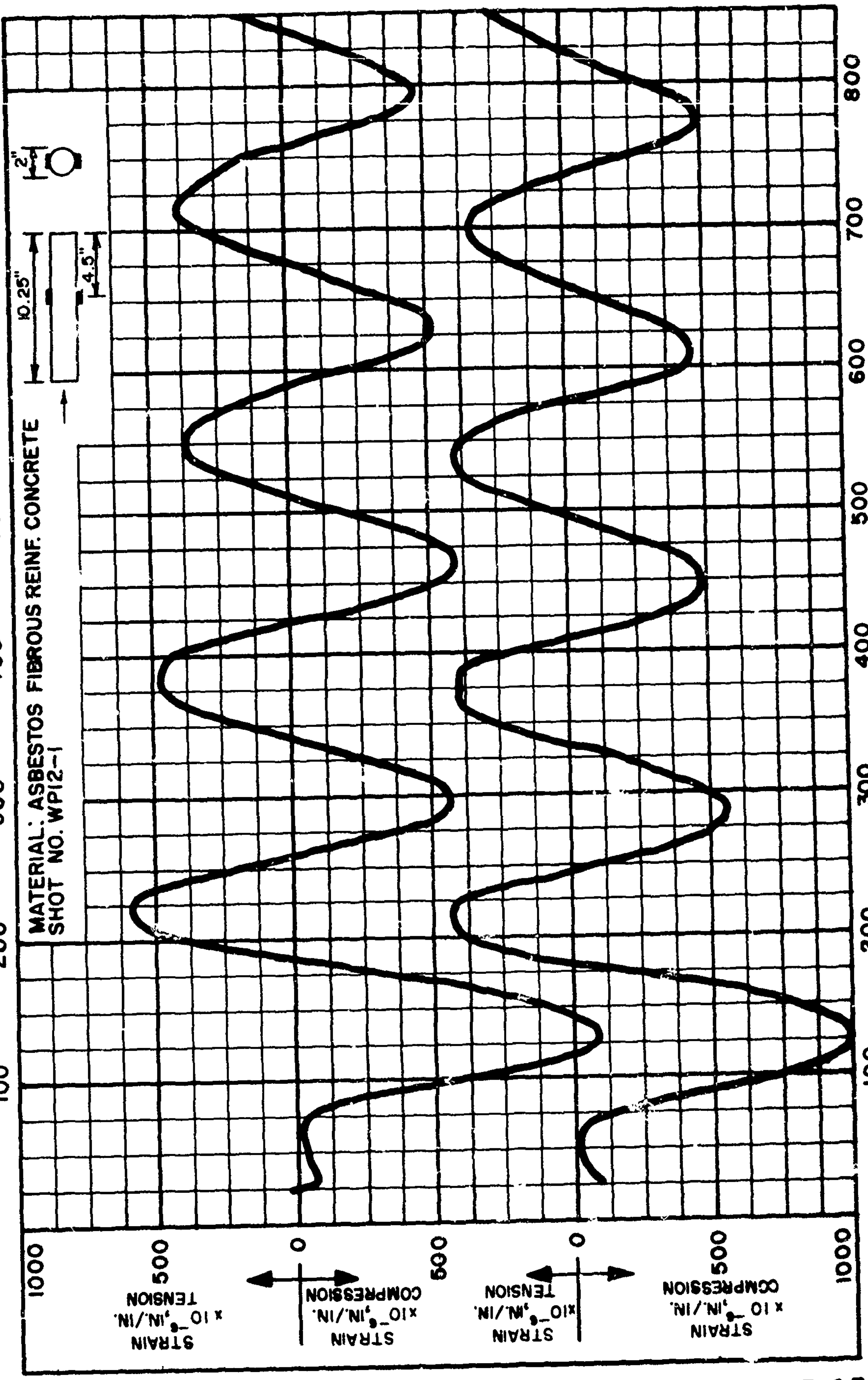
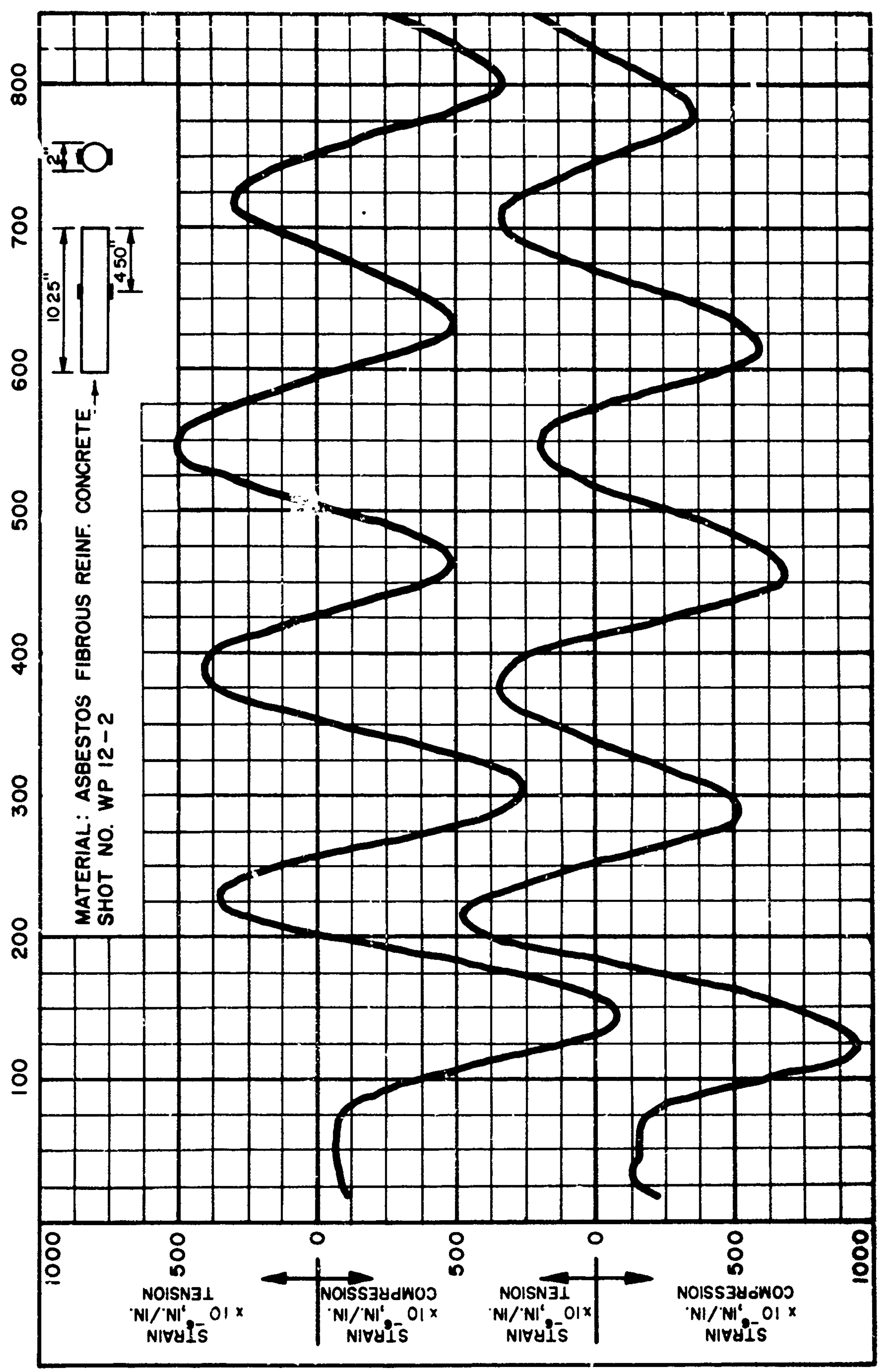

MATERIAL: ASBESTOS FIBROUS REINF. CONCRETE
SHOT NO. WP12-1
10.25"
4.5"
2"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
STRAIN x 10^-6 IN./IN.
TENSION
COMPRESSION
1000
500
0
500
0
500
1000

FIGURE 25



MATERIAL: ASBESTOS FIBROUS REINF. CONCRETE
SHOT NO. WP 12-2
10.25"
4.50"
2"
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
STRAIN x 10^-6 IN./IN. TENSION
STRAIN x 10^-6 IN./IN. COMPRESSION
1000
500
0
500
0
500
1000
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)

FIGURE 26

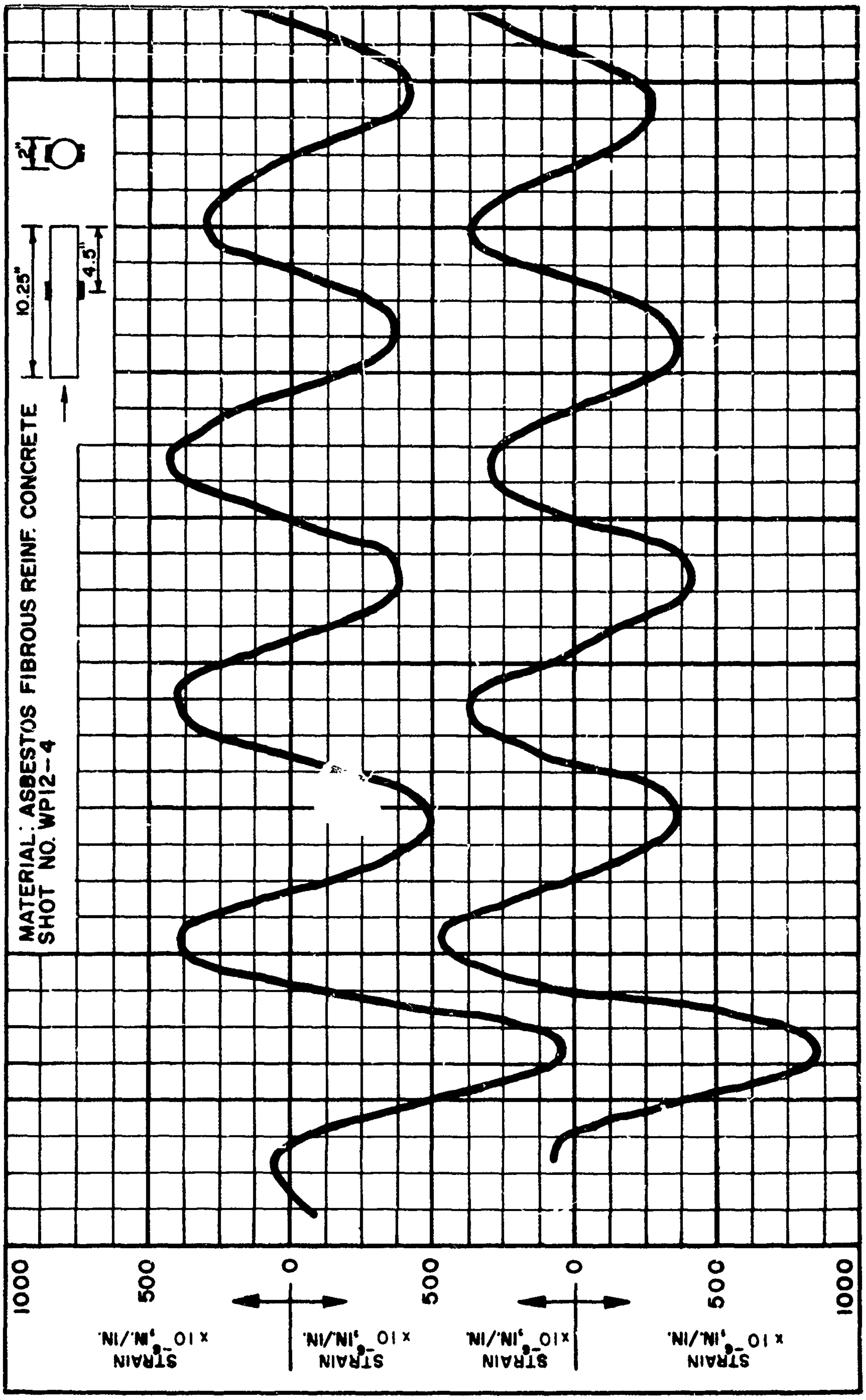

MATERIAL: ASBESTOS FIBROUS REINF. CONCRETE
SHOT NO. WP12-4
10.25"
4.5"
2"
TIME (MICROSECONDS)
100
200
300
400
500
600
700
800
STRAIN x 10^{-6} IN./IN.
1000
500
0

FIGURE 27

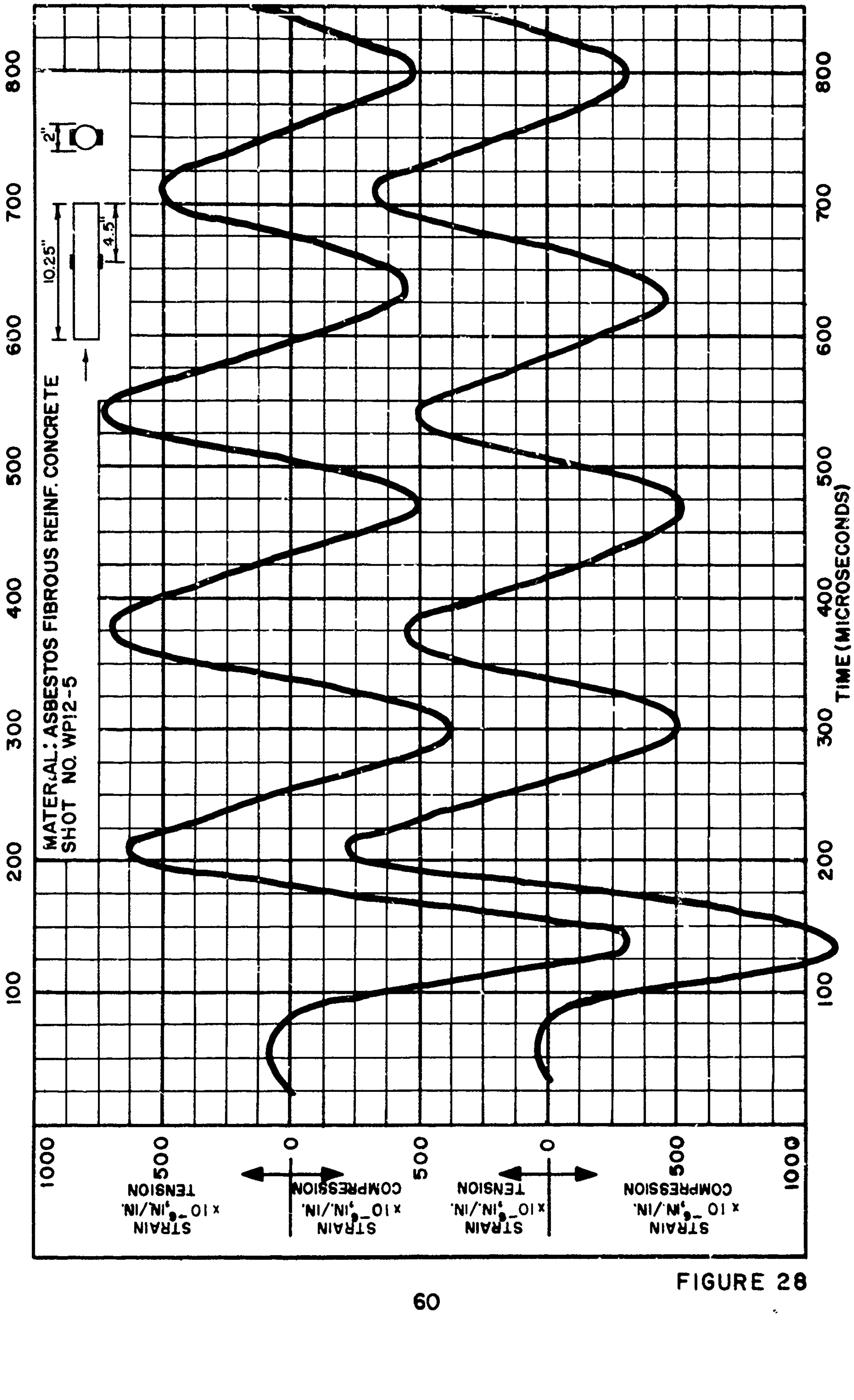
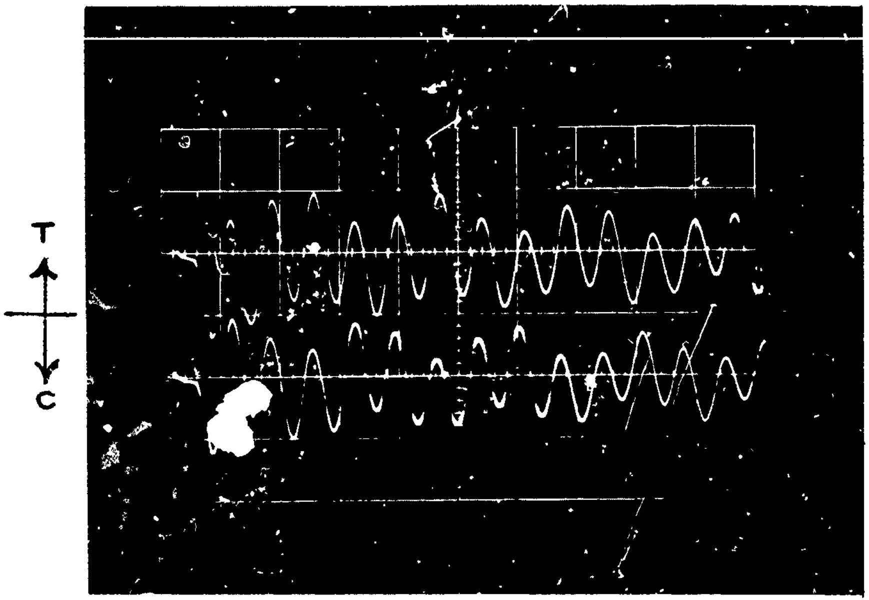

MATERIAL: ASBESTOS FIBROUS REINF. CONCRETE
SHOT NO. WP12-5
10.25"
4.5"
2"
100
200
300
400
500
600
700
800
TIME (MICROSECONDS)
1000
500
0
500
0
500
1000
STRAIN x 10^-6 IN./IN.
TENSION
COMPRESSION

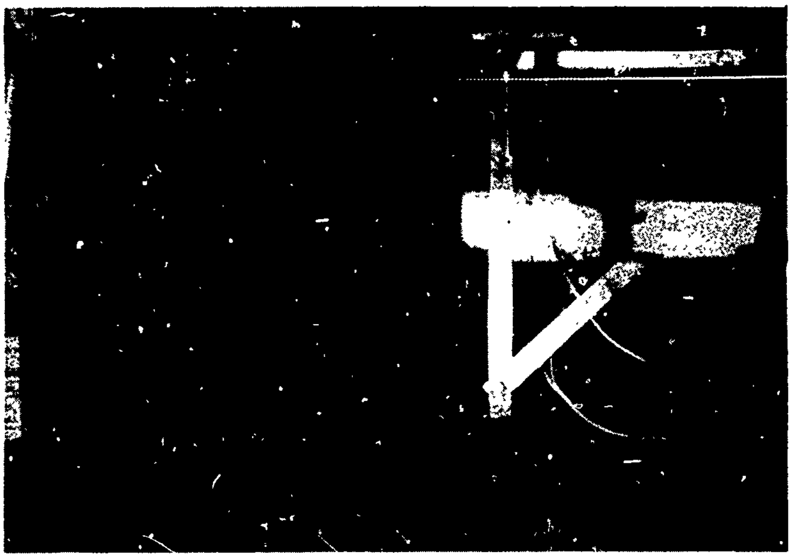
FIGURE 28



SR4 Calibration
500 Microstrains/cm
200 Microseconds/cm

Strain = 350 Micro-inches per inch

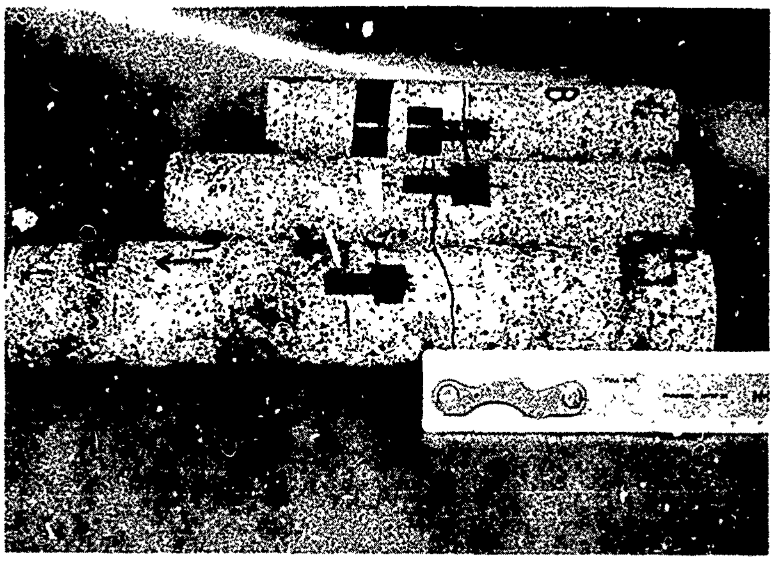
a Shot Wp7-1, Strain - Time Curve for Plain Concrete Specimen



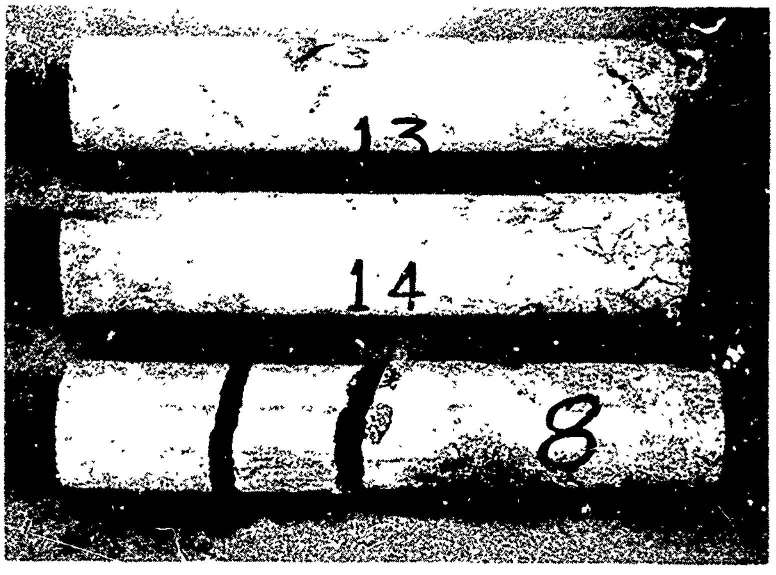
Strobe: 200 cps
Pellet
Velocity = 9.2 fps

Strain = 360 Micro-inches per inch

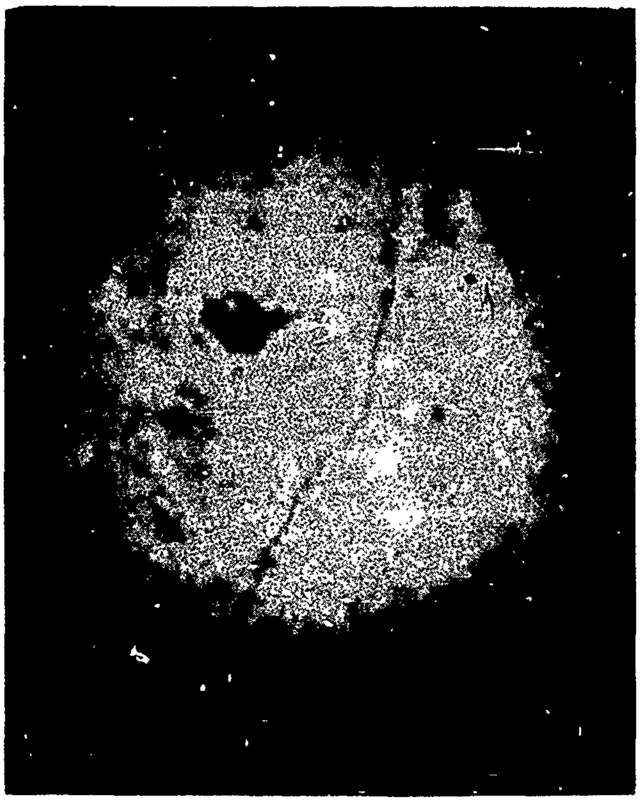
b Shot Wp7-1, Pellet Trace for Calculation of Strain in Plain Concrete Specimen



a Typical Quartz Monzonite Failures - Impact is from left side



b Typical Failure in Plain and Fibrous-Reinforced Concrete. Impact is from Right Side. Note Hairline Fractures Produced in Fibrous-Reinforced Specimens 13 and 14. Note Double Spall Produced in Plain Concrete Specimen 8.



Photomicrograph of Hairline Fracture Produced in Fibrous-Reinforced Concrete Specimen. (Magnified 20 Times)

APPENDIX A
IMPACT LOADING DEVICE

1. The initial air-fired projectile impact loader, described in a previous paper[7], used to induce a shock wave in a test specimen consisted of a lucite tube 2.75 inches in diameter and 36 inches long, coupled to a mechanism housing a diaphragm and a diaphragm-rupturing device. The air was supplied through a 2.5-inch diameter rubber hose, 48 inches long, which also acted as a storage tank. An electro-mechanical knife was used to rupture the oven-dried Repolith thin-base film diaphragms. A 150-psi gage was connected to the pressure side of the diaphragm to control the projectile velocities.

2. The need for closer control of the experiments dictated the necessity of improving the impact loader. The new equipment consisted of a lucite tube 2.5 inches in diameter and 36 inches long, coupled to a diaphragm housing and an air storage tank. An electro-mechanical pointed plunger is housed within the storage tank for rupturing the diaphragms. This eliminated the need for oven-dried diaphragms. The air is supplied through a rubber hose to the storage tank. A new pressure gage was installed with a 160-psi capacity, and calibrated so that interpolation to the nearest 1 psi could be made. This facilitated control of the projectile velocity at the end of the tube. The relation between pressure and the projectile velocity at the end of the tube is shown in Figure A-1. Holes were drilled in the lucite tube, every 3 inches, along its length to enable the positioning of a proximity probe along the tube. The air-fired projectile impact loader is shown in Plate A-1a.

3. The projectile is made of two pieces of aluminum 2.25 inches in diameter, and separated by a piece of hardwood 1.0 inch in diameter and two pieces of fiberboard 2.5 inches in diameter. The overall length of the projectile is 4 1/8 inches, and the total wieght is 250 grams. The impact end is bullet shaped. This configuration of a projectile evolved after trying many other types, and was finally decided upon because of its durability and low weight. The weight of the projectile can easily be changed simply by altering the size or type of the backing plate (see Plate A-1b). The relationship between the pressure and velocity for this projectile is given on Figure A-1.

4. Auxiliary equipment used to measure pellet velocities consisted of a polaroid camera, a dimensioned scale, a strob light, a Universal Eput and Timer, a proximity probe, and a ballistic support system for the cylindrical test specimen with the attached pellet. The pellet, weighing a few grams, is characteristic impedance-matched to the material of the test specimen. The complete test setup is shown on Plate A-1a.

CALIBRATION CURVE
AIR-FIRED PROJECTILE SHOCK LOADER
VELOCITY OF PROJECTILE VS FIRING PRESSURE

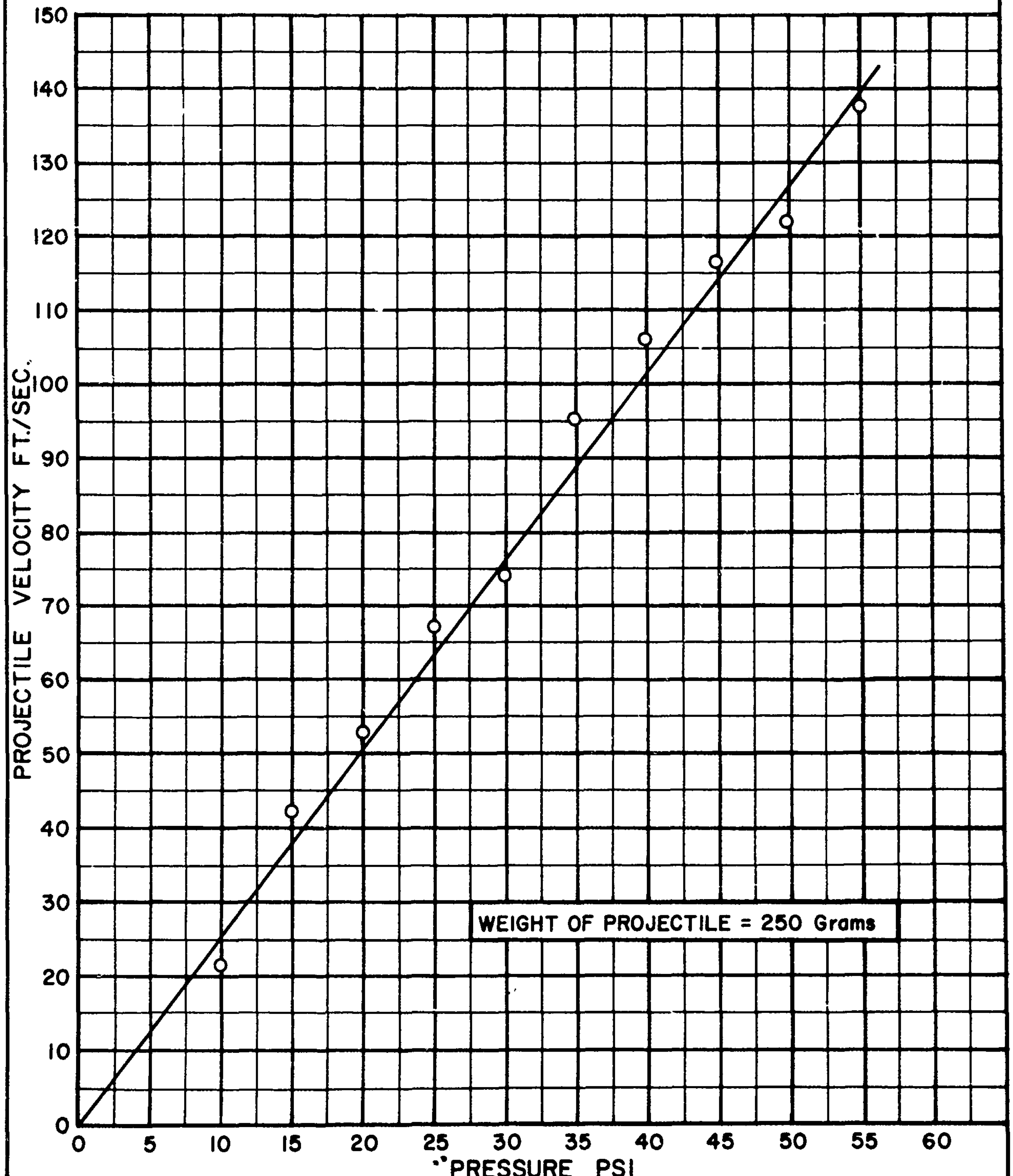
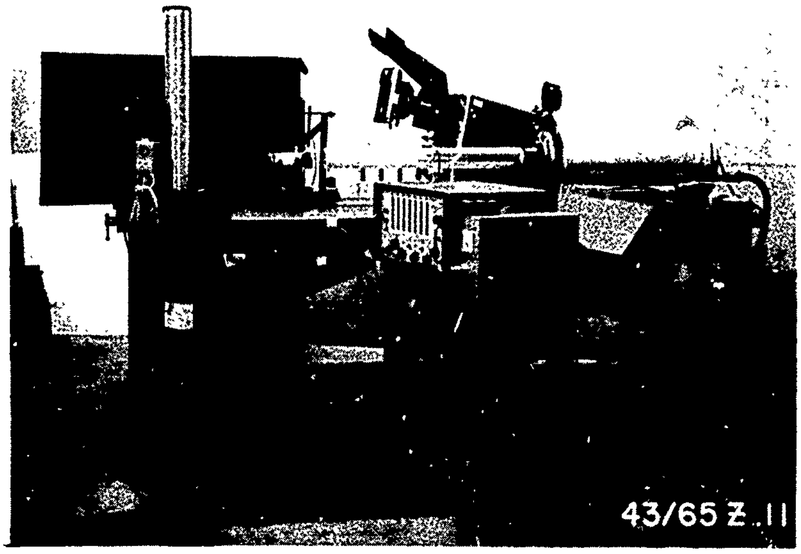
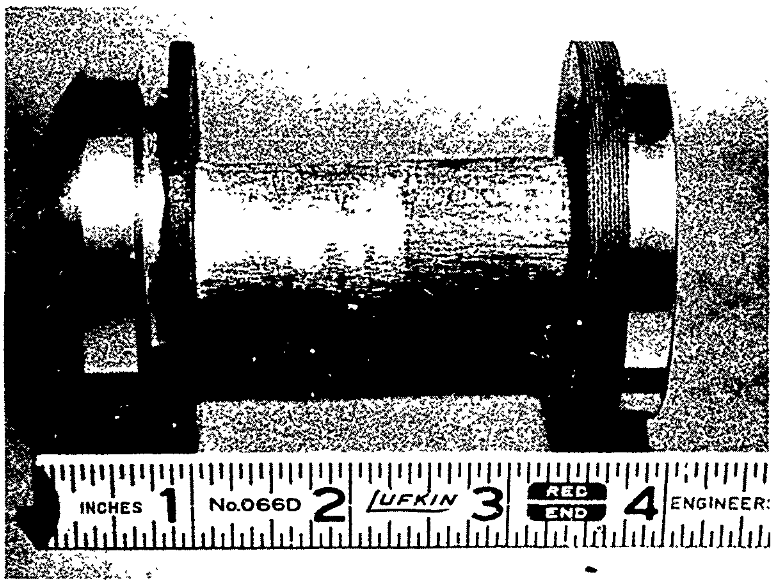


FIGURE A-1



a Overall View of the Air-Fired Projectile Shock Loader



b 250-gram Projectile

APPENDIX B
STRAIN MEASURING APPARATUS

1. Electronic measurements of strains on the surface of the test specimens under impact loading were made using a strain-gage system. The basic elements of this system consist of foil-type strain-gage transducers, bridge balance circuits, power supplied, high gain DC amplifiers, a fast rise-time oscilloscope, and an oscilloscope recording camera. Plate B-1 is a photograph of this apparatus. A block diagram of the overall system is shown on Figure B-1. The maximum number of recording data channels used was seven.

2. The strain gages used for these applications were W. T. Beans "Micro Measurements", gage type EA-13-250BB-120, which are temperature-compensated to 13 parts per million. This is reasonably close to the coefficient of thermal expansion of the material being tested. The gage is constructed of a foil-grid mounted on a flexible epoxy carrier. The physical dimensions of the gage were 0.49-inch overall length, 0.25-inch actual gage length, 0.175-inch overall width, and 0.175-inch grid width. The overall gage thickness was 0.0012 inches $\pm$ 0.0002 inches. The epoxy carrier is capable of elongation of up to 25%; while the gage element will measure strains up to 5% (50,000 micro-strains) with an accuracy of $\pm$ 3% of the induced strain. Extreme care must be exercised in preparing the surface of the specimen for the transducer. A standard gage resistance of 120 ohms was chosen for compatability with the bridge calibration system.

3. The bridge balance system was a standard Wheatstone bridge with three internal arms to complete the bridge. The balance system contained the balance circuit, a built-in shunt calibration, and gage span control. The bridge excitation voltages were provided by a regulated DC power supply.

4. Amplification of the strain gage signal was accomplished by the use of high gain differential DC amplifiers. The amplifiers used had the following applicable specifications:

Linearity: $\pm$ 0.01%

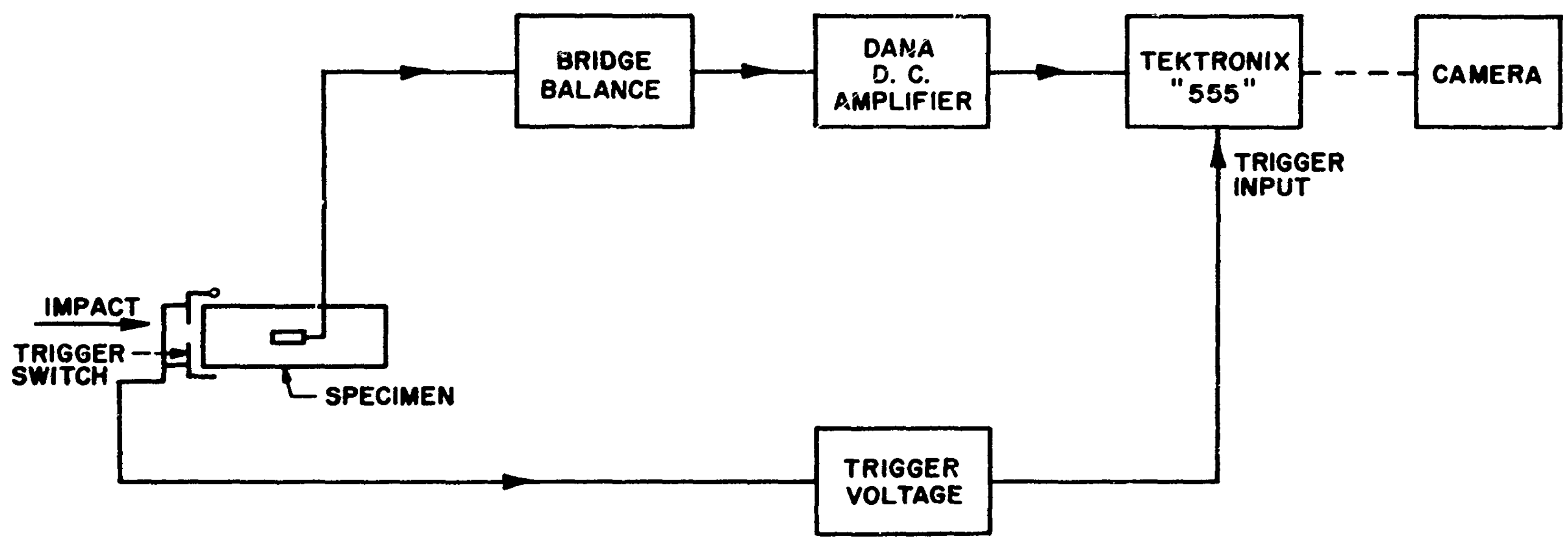
Gain: x10 to x1000

Bandwidth: $\pm$ 1 db.; 0-20,000 cycles/sec.

5. The strain signals from the amplifiers were displayed on a Tektronix 555 oscilloscope, using a type "L" fast rise-time plug-in preamplifier. This unit is capable of displaying transient signals with a rise time of 15 nanoseconds, and a frequency rate of up to 30 megacycles. A "one-shot" triggering device enables one to couple the scope to an outside event in order to display the information in one trace. A polaroid camera attached to the oscilloscope was used to record the output.

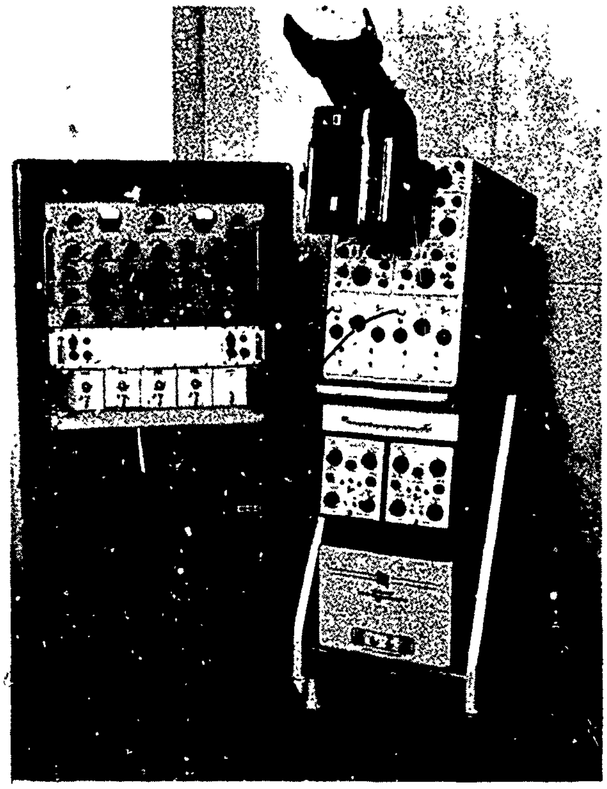
6. Using this equipment, the strain existing at a transducer location was measured with respect to time. This also gave an indication of the rise time of the actual wave.

ARRANGEMENT OF APPARATUS
FOR MEASURING LONGITUDINAL STRAIN IN A CYLINDRICAL
TEST SPECIMEN UNDER IMPACT LOADING



BLOCK DIAGRAM

FIGURE B-1



View of Electronic Signal Conditioning Equipment, at Left; and Tektronix "555" Oscilloscope with Camera Mounted, at Right

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3 REPORT TITLE

Measurements of Stress and Strain on Cylindrical Test Specimens of Rock and Concrete Under Impact Loading.

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5 AUTHOR(S) *(Last name, first name, initial)*

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13 ABSTRACT

A test method to determine the minimum dynamic tensional stress required to rupture materials that have a high compressive strength and a relatively low tensile strength is evaluated. The test loading is by impact from an air-fired projectile. The loading device utilizes a 250-gram projectile, and can produce an impact momentum varying from zero to over three pound-seconds. The rise time of the stressing pulse or shock wave produced in the test pieces is in the order to 20 to 30 microseconds, and the pulse length about 10 inches. The test method considered is based on the measurement of the velocity imparted to a pellet lightly attached to the distal end of a cylindrical test specimen subjected to the impact of an air-fired projectile. This velocity measurement provides the basis for computing the maximum longitudinal stress or strain created in the test specimen by the impact loading. The validity of this test method, which is designated as the "Pellet Technique", is evaluated by attaching strain gages to the test specimens and comparing this direct measurement of maximum longitudinal strain with that indicated by the pellet technique. Comparative measurements of this type were made on cylindrical test specimens of aluminum, quartz monzonite rock, plain concrete, and fibrous-reinforced concrete. There was good correlation between the strains measured directly and those obtained by means of the pellet technique. It is concluded, within certain limitations, that the pellet technique can be used to obtain quantitative values of the dynamic tensile strength for materials that have high compressive strength and relatively low tensile strength.

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Rock						
Concrete						
Fibrous Reinforced Concrete						
Strain Gages						

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